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Wind Action

Physiography

Issued June 15, 1911.

U. S. DEPARTMENT OF AGRICULTURE,

BUREAU OF SOILS—BULLETIN NO. 68.

MILTON WHITNEY, Chief.

THE MOVEMENT OF SOIL MATERIAL BY THE WIND,

By E. E. FREE

WITH A

BIBLIOGRAPHY OF EOLIAN GEOLOGY,

By S. C. STUNTZ AND E. E. FREE.

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LETTER OF TRANSMITTAL.

U. S. DEPARTMENT OF AGRICULTURE,
BUREAU OF SOILS,
Washington, D. C., January 19, 1910.

SIR: I have the honor to transmit herewith the manuscript of an article entitled "The Movement of Soil Material by the Wind," by E. E. Free, of this Bureau, with a bibliography of Eolian geology by S. C. Stuntz and E. E. Free. This article comprises an exhaustive review of the literature covering the subject, as well as the results of studies in the laboratory and in the field, both by the author and other members of the laboratory force. I recommend that this article be published as Bulletin No. 68 of the Bureau of Soils.

Very respectfully,

MILTON WHITNEY,
Chief of Bureau.

Hon. JAMES WILSON,
Secretary of Agriculture.

PREFACE.

The relation of the soil to crop production has always been regarded as the fundamental problem of agricultural investigation. It has inspired numerous researches and led to the production of an enormous literature. By far the greater part of these researches and their accompanying literature have been dominated by a theory, which has been conveniently designated as the "plant-food theory of fertilizers," but which may be defined more precisely as follows: The predominating factor in the production of a crop is the amount of available mineral plant nutrients in the soil. The primary purpose of this theory is to account for the results produced by the use of soil amendments, or fertilizers and manures. It presupposes that a given field or soil mass stays in place indefinitely, and without changes, except for such local ones as may be produced by cultural methods, or the removal of plant nutrients in garnered crops and seepage waters. The chief merit of the theory is its simplicity. Recent investigation and analysis of the problem have shown, however, that no such simple theory can be satisfactory; that many factors enter into the production of crops, or, in other words, the efficiency of the plant depends on numerous factors. The prominent characteristic of all these factors, including the soil factors, is that they are constantly in processes of change. In other words, the problem is dynamic rather than static.

Considering the soil factor, or more properly, factors, it is now clearly recognized that the living plant, or at least that part of it in the soil, the root, is always in motion while the plant lives. The soil solution, the natural nutrient medium for plants, is always in motion; for when water falls upon the soil there is always a movement into and through the larger soil interstices, mainly by gravity, and when the precipitation ceases there is immediately surface evaporation accompanied by a return to the surface of a portion of the absorbed water through the capillary interstices and in films over the soil grains. In like manner, the soil atmosphere is constantly changing, and it is obvious that the life of insects, bacteria, etc., in the soil is a process of growth and decay, and therefore of constant change.

The solid particles of the soil are likewise always in motion. The activities of insects, crawfish, earthworms, burrowing animals, etc.,

in translocating soil material are now recognized as being, in the aggregate, very large. Freezing and thawing produce considerable motion of soil material. It has recently been shown that every change in the moisture content of a soil is accompanied by necessary movements of the soil particles, and by changes in their state of aggregation, and it is obvious that under field conditions a soil is always either drying out or being wetted.

Besides these movements of the solid soil particles, resulting in profound changes from time to time, not the least of which is an interchange of the material between soil and subsoil, there is constantly in process a translocation of soil material from field to field, from area to area, and frequently over large distances. As a result, soils are notably complex as regards their composition—more complex by far than the individual rocks or rock magmas from which they have been derived; and, speaking generally, practically all soils contain all or nearly all of the common rock-forming minerals. To produce this state of affairs, two natural agencies are competent—water and wind. The effect of water action in translocating soil material is enormous, but restricted by the facts that water can run "down hill" only, and is but occasionally in action. The effects of wind action are quite as important, for the wind is constantly in action, to a greater or lesser extent, and blows up hill as well as down. While the effects of water action may be more striking and impressive, the effects of wind action are quite as important, from the point of view of the student of soils, if not of the surface geologist.

The activity of the wind as a geologic agent has long been recognized, and frequent descriptions exist of various phases of its activity. But its action on the soil has not received that amount and character of attention which both the practical and theoretical importance of the phenomena would seem to demand. Particularly is this so in that observations have been made with reference to strictly geological rather than agronomic considerations, and attention has been confined mainly to but a few and generally minor locations of strictly eolian soils.

It is clear that not only has the wind been a most important agent in the past in soil translocation, but that it is equally important to-day, not only in forming and modifying great deposits and areas of soil, but in modifying and affecting more or less profoundly every farm and field. It is one of the most important factors in the complex system of soil movement affecting soil fertility. No fact in our knowledge of the soil is now more clearly defined than that the soil of a particular field is not just the soil that was there a few years ago, or just the soil that will be there a few years hence. Moreover, it appears that when this translocation is at a "normal" it is beneficial and an important factor in maintaining fertility. But

when excessive, "wind erosion" is one of the most baneful of the farmers' troubles. Its prevention and control is therefore one of the great practical problems of agriculture, one easily met in the majority of cases, but sadly neglected, nevertheless.

Methods for controlling the action of the wind must be devised. Windbreaks, cover crops, rotation schemes, cultural, and other methods are actually in use to this end, more or less successfully. But in few localities can it be claimed that the problems have been met with complete success, and an unusual opportunity is open for experimental work of a most useful kind. In the following pages attention is called to the specific methods now in use, and it is felt that the discussion of the subject as given in the bulletin as a whole will be a useful step forward in the working out of practical methods of soil control in this field. Not alone to the tiller of the soil is this a matter of great economic importance, but to the railroads, the public highways, and irrigation works it is of great, and in some cases, paramount importance.

Important as is the action of the wind in removing soil material, and replacing it anew with material from elsewhere in all localities, it is especially so in arid and semiarid regions. Here control is not so easy, and in fact wind action is in many areas of the arid portions of the United States the all-important problem determining the possibility of settlement and utilization of the soils. Here at least the subject is by no means of merely academic interest, but is of the greatest immediate importance.

In view of the facts presented above it has been deemed necessary to bring together, correlate, and summarize the known data of eolian geology from the viewpoint of the student of soils. This Mr. Free has done, the results of his work being given in the following pages. These include not only the results of a very comprehensive review of the literature but many of his own observations, made in many cases to clear up obscure points or apparent discrepancies in the work of previous observers. In the preparation of the bibliography the skill and experience of Mr. Stuntz have been available, so that it may be regarded as fairly complete, it being improbable that any citation of importance has been overlooked. It is believed that the present bulletin will prove to be one of the most important in the series which has been published from the Bureau of Soils on the fundamental principles of soil formation and soil control.

FRANK K. CAMERON.

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THE MOVEMENT OF SOIL MATERIAL BY THE WIND.

THE HETEROGENEITY OF SOILS.[a]

Recent work in this Bureau and elsewhere has indicated [b] that the normal soils in the most diverse regions are remarkably similar, in that all of the important soil-forming minerals are present therein in greater or lesser quantity. This similarity in the constituents of all soils is of course largely due to the fact that they are formed everywhere under much the same conditions and from materials of the same general character,[c] namely, the rocks. The original igneous rocks contain in most cases all of the minerals important in soil formation, and since most sedimentary rocks are secondary deposits, derived from igneous originals, they also contain the important soil minerals. It should be noted that it is not necessary for the soil minerals to exist in large quantity in the parent rock. The soil is usually the residuum from the decay of a much greater thickness of rock, and there are some evidences that there is in the processes of soil formation a tendency for the retention and concentration of the various minor rock constituents, in spite of the fact that their proper rates of disintegration may be greater than those of the other, more prevalent, minerals. If this be so the normal processes of soil formation will tend to maintain and to increase heterogeneity and the soil will be likely to con-

[a] AUTHOR'S NOTE.—Throughout the following pages the attempt has been made to cite authorities whenever possible and to give references to all important and pertinent literature. All quoted articles are given in the appended bibliography, and readers interested in the literature are advised to refer at once to page 174, where the system of citation is explained.

The author wishes also to acknowledge the general assistance and suggestions of the many persons who during the past three years have encouraged and helped the development of the ideas of which this bulletin is the fruit. Especially should an acknowledgment be made to Dr. D. T. MacDougal and Prof. C. F. Tolman, jr., of Tucson, Ariz.; Prof. J. A. Udden, of Rock Island, Ill.; Mr. J. M. Westgate of the Bureau of Plant Industry; and Drs. F. K. Cameron and W J McGee of the Bureau of Soils. The assistance of Mr. Stuntz has not been confined to the bibliography which bears his name, but has been felt on every page of the text. To all these gentlemen and to many others whose assistance it is impossible to acknowledge in detail, any excellence which this work may possess is largely to be ascribed.

[b] Bull. 30, Bureau of Soils, U. S. Dept. Agr., p. 9–11 (1905), and references there cited; also Bull. 54, Bureau of Soils (1908).

[c] The general processes of soil formation are discussed in all text-books on soils. See especially Merrill—Rocks, rock-weathering, and soils (1906).

tain, not only all of the minerals present in the parent rock, but to contain certain of the minor constituents in considerably increased proportions. If, however, disintegration be carried too far, this heterogeneity will be destroyed, because in the last analysis the persistence of a mineral in the soil depends on its capacity of resisting the disintegrating agents. An easily disintegrated mineral may be protected for a time, perhaps by the presence of much other material, but it must ultimately succumb. Thus a soil exposed to the weathering agents without the supply of new and unweathered material must come to be composed of its most resistant mineral in a more or less pure state, and since quartz is the most resistant of the ordinary soil minerals,[a] the ordinary result of complete weathering of the soil is pure quartz. This actually does occur in special cases where the agencies of removal[b] are much more active than are those which supply unweathered material. Clarke[c] mentions a beach sand which contained 99.65 per cent SiO_2, and the present writer has examined sands in which absolutely no mineral other than quartz could be detected by microscopic examination, though traces of other elements, especially iron, could usually be found by chemical means. Under desert conditions the products of mineral disintegration are so rapidly removed by the wind that in the older deserts the surface material is quartz sand of great purity.[d]

That such occurrences are not more frequent is due to the fact that under normal conditions new material is supplied as rapidly as the old is removed. Undecomposed rock fragments are brought up from below and carried in from a distance by means of the various translocating agents, and the composition of the soil is kept fairly constant. In most cases also the mechanical removal of the entire soil is so much more rapid than the differential removal of the more easily disintegrated minerals that the processes which tend to make the soil more siliceous do not have time to show their effects. This material mechanically removed is replaced, so far as the soil is concerned, by

[a] This means only that quartz is the most resistant in the majority of cases, and wherever the weathering agents—chemical and mechanical—are normally balanced. To chemical erosion (by solution) quartz is not so resistant as are the various oxides and hydroxides of iron, and if erosion were anywhere exclusively chemical the soil would then become not siliceous, but ferruginous. This case is approached in certain sections of the tropics and laterites high in iron have been there produced. The iron compounds are, however, very easily disintegrated into minute fragments and are therefore unusually susceptible to removal by the agents of mechanical erosion (both eolian and aqueous). In all ordinary cases therefore the iron is removed mechanically as fast as or faster than the quartz is removed chemically, and it is only under conditions which limit or inhibit the mechanical agencies that quartz loses its supremacy of persistence.

[b] Mechanical, of course. See note *a*.

[c] U. S. Geol. surv. Bull. **330**: 427 (1908).

[d] Walther—Wüstenbildung, chap. 9 (1900). On the silicification of sand by water transport see Mackie—Trans. Edinb. geol. soc. **7**: 148–151 (1897).

freshly disintegrated rock from below and by the translocation of the surface material. The persistence of the soil is, as probably first pointed out by Élie de Beaumont,[a] rather a persistence of the soil layer than of the individual particles. It can not be too much emphasized that the soil is always in process of change, and that soil conditions are not static but dynamic.[b]

Practically all writers [c] on the subject have noted the existence of extensive areas of soil composed largely or entirely of transported material. Shaler [d] estimates that the truly alluvial soils in North America cover an area of over 200,000 square miles, and much greater areas are covered by soils which are in part of alluvial origin. It is much more common to find lack of conformity between the soil and the underlying rock than it is to find the one strictly derived from the other.

Not only are many soils thus composed in whole or in large part of transported material, but even in soils which are clearly residual there is frequently much foreign material. "Almost all soils, except those on very level plains, have derived their mineral parts in some measure from the rocks which do not lie immediately beneath their site." [e]

The observed heterogeneity of soils is therefore due both to the nature of the processes of rock disintegration and to the mixing of one soil with another, which is brought about by the various transporting agencies. The weathering agents alone could not permanently maintain the heterogeneity of the soil without the assistance and continued activity of the transporting agents; and, since the fertility of the soil depends on the existence therein of all the soil minerals, the great importance of these agencies of transportation is evident.

TRANSLOCATING AGENTS IN GENERAL.

There are two general ways in which soils are mixed: (1) Vertical translocation, mainly the bringing up of material from the subsoil or below, and (2) lateral translocation, or the moving to one area of soil material from some other area. The first is, of course, local and can not supply to the soil anything not present in the parent rock or other underlying material, though it is extremely important in preventing the deterioration of the soil which might result from excessive weathering. The second process may be either local or general, and is not limited as to sources of material or distances of transport. Exact discrimination in individual cases between vertical and lateral trans-

[a] Leçons de géologie pratique, vol. 1, p. 140 (1847).

[b] Cameron—Jour. indust. and eng. chem. 1: 806–810 (1909).

[c] See, for instance Johnston—Application of chemistry and geology to agriculture, pp. 267–268 (1859); Shaler—Ann. Rept. U. S. Geol. Surv. 12: 287–306 (1891); Merrill—Rocks, rock-weathering, and soils, part IV (1906); Hilgard—Soils, chap. I (1906).

[d] Loc. cit., p. 291.

[e] Shaler—loc. cit., p. 296.

location is neither possible nor desirable. Both are constantly occurring side by side, and both are most necessary to the continued good condition of the soil.

The most important agents in the vertical—and therefore local—translocation of soils are the movements of plants and animals and the operations of agriculture. When plants, especially trees, are uprooted by the wind or other agency, their roots carry with them to the surface considerable quantities of lower soil, and the space thus left is slowly filled with surrounding surficial material. In humid climates the most important of the animal agencies is probably that of the ordinary earthworm, as was pointed out by Darwin [a] in 1837. He estimates [b] that in places they produce on the surface an accumulation of 0.2 inch annually. The similar action of ants and termites has been observed by Mills,[c] Branner,[d] and Knab[e] in Brazil, and by Shaler [f] in New England, and the various species of crawfish, as well as the larger burrowing animals—moles, rabbits, and prairie dogs—are doubtless also of importance.[g]

A certain amount of translocation, both vertical and lateral, is produced by the slow creep of soil on slopes under the action of frost, changes of temperature, falling rain, etc.,[h] and by the gravitational fall of particles to lower levels. More rapid transfer is produced in occasional slips, landslides, etc. It seems certain also that the soil particles themselves are continually in motion,[i] though the amount of translocation produced by this means is probably very small.

---

[a] Proc. Geol. soc. London **2**: 574–576 (1838); Trans. Geol. soc. London (2) **5**: 505–510 (1840). His researches are given in extended form in his "Formation of vegetable mould," 1881. See also Henry—Bull. Soc. Sci. Nancy (3) **1**: 23–34 (1900).

[b] Formation of vegetable mould, New York, 1898, p. 307.

[c] Amer. geol. **3**: 351–357 (1889).

[d] Bull. Geol. soc. Amer. **7**: 295–300 (1896); and Jour. geol. **8**: 151–153 (1900).

[e] Science (n. s.) **30**: 574–575 (1909).

[f] Ann. rept. U. S. Geol. Surv. **12**: 278 (1892). See also Kinahan—Geol. mag. **6**: 348 (1869); Hensen—Zs. wiss. Zool. **28**: 354–364 (1877); Key—Nature **17**: 28 (1877); Holmgren—Zool. Jahrb. Abt. Syst. **20**: 353–370 (1904); Hilgard—Science (n. s.) **21**: 551–552 (1905); Headlee and Dean—Kans. agr. expt. stat. Bull. **154**: 165–180 (1908).

[g] A good account of the action of plants and animals in moving the soil will be found in Shaler's monograph already cited, Ann. rept. U. S. Geol. Surv. **12**: 268–297 (1892).

[h] This process (called "solifluction") has been well described by Andersson, Jour. geol. **14**: 91–112 (1906).

[i] The main item of eyidence in favor of this conclusion is the fact that in most soils considerable changes in volume take place on wetting and drying. (See Bull. **50**, Bureau of Soils, U. S. Dept. Agr., pp. 27–45 (1908), where previous literature is summarized.) These volume changes are believed by Hilgard (Soils, p. 122) to be due to the peculiar properties of "colloidal clay," and by Cameron and Gallagher (Bull. **50**, just cited, p. 50) to be caused by changes in the moisture films surrounding the grains, with succeeding changes in the degree of "flocculation." Whatever their ultimate cause, it is evident that they must be accompanied by a considerable movement of the soil grains in relation to one another. It is possible that temperature changes may also produce some such movements.

More general in their sphere of action than the agencies above discussed are ice, water, and wind, which, since they act over extended areas, are capable of transporting soil material to considerable distances. Of these, ice has been much more active at certain times in the past than it is to-day. During the Glacial period the North American ice sheet scraped off much of the soil which had previously accumulated on the areas which it covered, and deposited it over the lands and in the seas to the south. At the present time translocation by ice is of minor importance except in the polar regions. Its manifestations elsewhere are confined to the action of drift ice and of glaciers; the latter being occasionally of moment in supplying silt to rivers. The importance of ice action to the student of present-day conditions lies in the existence of extensive deposits which have been largely produced through glacial agency, though that agency has now ceased to act. The North American ice sheet on its retreat left behind it a great amount of morainic material, while it discharged from its borders enormous quantities of finely comminuted rock, which was laid down by streams and in lakes and seas to form the soils of later epochs. These glacial soils, formed both under and beyond the ice sheet, are to-day very important agriculturally, and their origin has greatly affected their properties. This subject, however, is outside the scope of the present discussion.

The action of running water in transporting all manner of rock detritus is a matter of common knowledge. Indeed water is usually considered the only translocating agent of much importance, and, while this conclusion is not justifiable, it is possible that a greater actual quantity of soil material (and other detritus) is moved by water than by any other one agent. In addition, too, to its more extended and better known action as instanced by transfer in rivers, etc., water produces much local mixing and moving of soils, both vertically and laterally. It is probable that there is some tendency for the finer material of a soil to wash downward through the interspaces under the action of percolating rain water,[a] and the lateral movement is seen in the wash of surface soil by rain storms. Every little rill carries its quota of soil particles and distributes them at lower levels. The amounts concerned are small and may seem unimportant, but every rain does its part, and the aggregate results are large. Exactly similar to the action of rain on the soil, though on a larger scale, is the wash occasioned by heavy storms in mountainous

[a] See Hilgard—Soils, p. 161 (1906), and Hull—Oorsprong der Hollandsche duinen, p. 103 (1838). However, some preliminary experiments (as yet unpublished) conducted several years ago at Cornell University by Mr. C. F. Shaw, under the direction of Dr. J. A. Bonsteel, failed to show any tendency for the clay to accumulate in the lower layers of a soil through which over 100 inches of water was percolated. It is possible that the downward infiltration of clay is not so common as has been believed.

regions, producing alluvial fans of material carried down mountain slopes in the same way that soil material is carried down the irregularities of a field. Small-scale examples can be seen everywhere after a moderately heavy rain storm. The Brick Earth of southern England is an extensive deposit believed to have been formed by rain wash,[a] and similar deposits occur in many other localities.

The transporting action of small streams is both more extended and more restricted than that of rills formed by the rain. Streams run all the time, but this apparent advantage is lost by their being confined to fixed channels. The rain, however, falls everywhere, and rain rills form over the whole of the uncovered surface, and hence have a much greater quantity of material exposed to their attack than can come under the action of permanent streams. Streams, on the other hand, because of their permanency, can carry material to much greater distances. Of course what actually happens is that the rain and the streams assist each other. The rain-water rills carry part of the surface soil into the small streams and these in turn to the rivers. Enormous quantities of silt are constantly in suspension in most rivers and streams,[b] and in the larger rivers even greater quantities are pushed along the bottom by the current.[c] Much of the transported material is thrown up along the bank and deposited on the bottom, but most of it goes out to sea, and the precipitation both of "bottom-drift" and of suspended material at the river's mouth supplies the material which makes up the delta. Delta lands, being composed of material derived from the whole drainage area of the river, are unusually heterogeneous, and when cultivation is possible remarkably fertile, as is indeed true of alluvial lands in general.

By rain wash and stream action, alone and together, the aggregate of soil translocation performed by running water is very great indeed. Yet this agent is by no means of universal action. Close examination will show that its activity is narrowly limited in several ways, some of which it will be advisable to discuss.

THE LIMITATIONS OF WATER TRANSLOCATION.

All water transportation is limited by two conditions prescribed by the nature of the action itself: (1) It can occur only from higher to lower levels, and (2) it can degrade or aggrade[d] only the surface with which the water comes actually in contact. Water-borne

[a] Godwin-Austen—Quart. jour. Geol. soc. **6**: 94 (1850), **7**: 121 (1851); Foster and Topley—ibid. **21**: 446 (1865); Prestwich—ibid. **48**: 323 (1892).

[b] See A. Geikie—Textbook of Geology, 4th ed., vol. **1**, pp. 488–489 (1903); Humphreys and Abbot—Physics and hydraulics of the Mississippi, 2d ed., pp. 147–149 (1876); Babb—Science **21**: 342–343 (1893); and especially the comprehensive tables of Dole and Stabler—U. S. Geol. surv. Water supp. pap. **234**: 84–93 (1909).

[c] Humphreys and Abbot—loc. cit., p. 147; Forshey—Proc. Amer. assoc. adv. sci. **26**: 144 (1877); Guérard—Proc. Inst. min. engs. **82**: 309 (1884–85).

[d] These words are used in their ordinary geological meanings. "Degrade" means to lower the level of the general land surface of the locality considered by removing material therefrom. "Aggrade" means to raise this surface by depositing material thereon.

detritus can be carried only down hill, and in ordinary cases the journey must be continuously downward. A barrier to the continuous fall of the water will effectually stop the progress of the suspended load, though the water itself, by backing up sufficiently, may be able to escape at a higher level. Lakes thus formed act as settling basins and the water escaping from them usually carries very little suspended matter, however much it may have borne on entrance. Of course, the material carried into a lake is laid down on its bottom and will (if the supply be kept up) ultimately suffice to fill it, so that the river will run through a flat plain where the lake once stood. When this happens the detrital load of the stream will be carried on to the next lake or to the sea.

The second limitation of water action is even more self-evident as applied to streams. It is obvious that running water can attack only the surface over which it runs, and equally obvious that it can deposit the material gained only on those surfaces which it is, at least occasionally, able to cover. This second limitation has, however, little force when applied to the action of rain water, for practically the whole surface is exposed to the action of rain. But rain water, like all running water, can act only down hill, and its action is still further limited by several special considerations. In the first place, rain water becomes effective as an eroding and transporting agent only when the precipitation is sufficiently rapid to exceed the rate of absorption by the soil, and thus to cause water to run on the surface. In most climates much of the annual rainfall comes in rains so gentle that the water is absorbed as fast as it falls, and very little, if any, runs over the surface outside of the fixed channels, natural and artificial. Such rains can have no great translocating action. Whether a particular rain storm will be sufficiently heavy to have any erosive action depends not alone on the actual rate of precipitation but on the absorptive power of the soil, and, in the case of long-continued rains, on the efficiency of the soil drainage. A rain which lasts long may finally bring the soil to a state approaching saturation, and then begin to have an erosive action, though it had none at first.

At best, rain-water translocation is of intermittent action. Rain storms of sufficient violence to have any appreciable effect are of only occasional occurrence in ordinary climates, and in many climates they are very rare indeed. The proportion of time in the year during which rain water is actually running over the surface in the ordinary humid areas is certainly less than 5 per cent. The heavy rains, which alone are active, are usually of short duration. Finally, rain-water translocation, as mentioned above, is essentially local. It may produce an effective mixing of the surface of any one field (provided conditions of slope are favorable) but further than this it can not go unassisted.

The sphere of river and stream action is in some ways even more limited, because, not alone must all action be down hill, but it must be on the relatively small surface actually reached by the water. The streams themselves can attack only their own beds, and were they dependent on their own resources for their supply of detrital material, it would be reduced to small fractions of that which they now carry. The bed, when once established, is usually attacked relatively slowly and the supply of material on the banks would soon be exhausted were it not kept up by other agents. Of course, as a matter of fact, streams are not dependent on their own exertions for their supply of detritus. Loose material is continually washed into them by the rain; and, where the bordering slopes are steep, much material falls and creeps into them under the action of gravity. However, rain wash, as just pointed out, is intermittent in its action, and soil creep affects only the soil immediately adjacent to the stream, and materially affects that only when the slopes are steep. Further, the access of detritus to the streams by either of these methods is in large measure prevented by a border of vegetation along the banks, and, owing to the plentiful supply of water which they furnish to the soil on their banks, all streams tend to produce such vegetal borders and thus themselves to limit the supply of detritus which reaches them. Always, however, to limit it, and never to shut it off entirely, since some eroded material will find its way in, in spite of all vegetal or other obstacles.

Some rivers (and occasionally smaller streams) are so situated that they are able to attack directly deposits of alluvial material which they themselves, or other rivers, have laid down in previous epochs. The lower Mississippi, the Ganges, the Yangtsekiang, and the Po, are examples. Such rivers are not limited to the action of rain water and of their smaller tributaries for their supply of suspended material, since they by their own action can obtain such material from their banks. Such a procedure, however, is but one step in the process of translocation. The alluvial material must have come from somewhere. The river has simply juggled it a bit before passing it finally into the sea. Material derived from the banks would not last forever, and in general what is taken away at one time or one place is replaced at another. The ultimate source of the river load is farther back. This is still true of the Chinese rivers, though the amount of alluvial material directly available is there so enormous that the river may be considered as having a practically inexhaustable supply of soil material always open to the attack of the stream itself. The loess [a] is so great in extent that eons will be required for its complete degradation. But the loess is not a primary material. It has already been subjected to much translocation, and the existence of this appar-

[a] On the Chinese loess, see p. 126 et seq.

ent exception does not shake the conclusion that rivers in general are greatly limited in their powers of attack, and require the assistance of other agents to complete their supply of detrital material.

But, by rain wash and stream movement acting together, the surface waters have a reasonably large range of attack. There are but few localities where the surface is not somewhat subject to the erosive action of water, and the suspended load of a river generally represents to some degree the soil of the whole of its drainage area; well enough at least to give river deposits all necessary heterogeneity. A much more serious limitation to the action of rivers and streams lies in their inability to deposit their load except where their waters actually flow. However well charged be the river water with the various soil forming materials, no benefit will accrue to the land lying higher than the flood level, and in nearly all river basins these lands far exceed in area and value those which are occasionally subject to flood.

The action of running water is limited, therefore, in that the streams are restricted, both in attack and deposition, to the surface actually covered; and in that the main source of supply of extraneous material to the streams, namely, rain wash, is very intermittent in its action. The most serious restriction is that of deposition, since never more than a small section of the land surface can under present conditions be subject to cover by flood waters. Larger soil areas may be found in which river deposition has played a part in the past, though it has long ceased to do so. Such are the alluvial lands in river bottoms, and on terraces, old flood plains, etc. When the product of large rivers, these are of course thoroughly mixed and very fertile, but they make up no large percentage of the available farm lands. Of the soils usually (and rightly) classed as alluvial, the larger proportion are the products of the present or past action of small streams, and the sediments of these streams, being derived from smaller and less diversified drainage areas, do not compare with river sediments in heterogeneity or fertilizing value. It is not probable that any major proportion of the present arable soil is now receiving or has received river or stream sediments of sufficient diversity to be of material assistance in the maintenance or increase of heterogeneity.

At the present day the one translocating action of water which is most important in the maintenance of heterogeneity and fertility is not the addition of new material to the soil, but the removal of old material from it. By the constant and normal removal of surficial soil through the streams into the lakes and oceans, the soil layer is pushed gradually into the underlying deposits, and secures therefrom fresh, unweathered, and unexhausted materials. In this way water translocation is of great and indubitable importance, but in the supply of new material by cross-surface translocation it must in all probability yield in importance to the action of the wind.

WIND TRANSLOCATION.

The importance of the wind as a geologic agent has been recognized by many geologists,[a] and its action on the soil has been noted in most general works on the subject.[b] In addition to these incidental notices, general papers on the geologic action of the wind have been published by Czerny,[c] Walther,[d] and Udden,[e] while Bychikhin,[f] Hensele,[g] Bĉletskĭĭ,[h] Engelhardt,[i] and Stahl-Schroeder[j] have written on the general action of wind on the soil.[k]

Most of these and other writers who have discussed the geological action of the wind have confined themselves in the main to the more striking examples of its work, as, e. g., sand dunes, dust and sand storms, the formation of extensive eolian deposits, etc. These phenomena are naturally the ones which most attract attention, because in them the agency of the wind is easily discernible, but, though geologically important, they are less often agriculturally so, since they occur mostly in the more arid regions, where extended agriculture is impossible. So much has attention been confined to these practically arid region phenomena that soil students in general consider the wind as specifically a desert agent and of little, if any, importance in the humid regions. This is by no means the case. It will be shown below that large quantities of soil material are everywhere being moved about by the winds, and this transfer, by assisting the mixing of soils, has been, and is, of the utmost importance to

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[a] Élie de Beaumont—Leçons de géologie pratique, vol. 1, pp. 183, 200 (1847); von Lasaulx—Encyclop. der Naturw., Abt. II 1: 68–80 (1882); Penck—Morphologie der Erdoberfläche, vol. 1, pp. 254–259 (1894); Lapparent—Leçons de géographie physique, 2d ed., pp. 249–261 (1898); Squinabol—Cenni di geografica fisica e di geologica, p. 32 et seq. (1900); A. Geikie—Textbook of geology, 4th ed. vol. 1, pp. 432–446 (1903); Chamberlin and Salisbury—Geology, vol. 1, pp. 20–39 (1904).

[b] See, e. g.: A. D. Hall—The soil, p. 10 (1903); Merrill—Rocks, rock-weathering, and soils, 2d ed., pp. 280–286 (1906); Burkett—Soils, pp. 15–16 (1907); S. W. Fletcher—Soils, pp. 18–20 (1907); Hilgard—Soils, pp. 8–10 (1906), etc.

[c] Peterm. Mitt. Ergänzungsh. 48, 1876.

[d] Abh. K. sächs. Ges. Wiss. Leipzig 16: 345–570 (1891); Himmel und Erde 10: 259–267, 301–311 (1898); and Das Gesetz der Wüstenbildung, 1900.

[e] Jour. geol. 2: 318–331 (1894), and The mechanical composition of wind deposits, Augustana Lib. Pub. No. 1, 1898.

[f] The influence of the wind on the soil (*Russian*), 1891; and Trudy Imp. vol. ekon. obshch. 1892: 312–390.

[g] Forsch. Geb. Agric.-Phys. 16: 311–364 (1893).

[h] Mat. izuch. russ. pochv 9: 1–40 (1895).

[i] Khozĭain 1895: 633–634.

[j] Poln. entsik. russ. selsk. khoz. 3: 163–175 (1900); Selsk. khoz. i lĉsov. 196: 363–378 (1900).

[k] A large part of these articles is devoted to the action of the wind on the moisture, gases, and temperature of the soil, subjects which are outside the scope of the present discussion.

agriculture. This constant drift of blown material has largely passed unnoticed,[a] because it does not of itself attract attention; its results are slowly produced, and when complete are difficult to distinguish from the results of other agencies. Where special conditions exist, special manifestations are developed; and these being unusual and striking, attract attention entirely out of proportion to their true importance. The wind must be considered as active everywhere. In a geological sense it is perhaps most active in arid regions, where the surface is dry and easily attacked and where protective vegetation is absent; but, agriculturally considered, its activity in humid regions is of much greater importance on account of the greater productive value of the lands affected.

It is, of course, true that the arid-region manifestations of wind action may indirectly affect the humid regions, as, e. g., when a dust storm originating in the Sahara carries material to Southern Europe, or when desert sands are blown into a river, to be deposited along its lower course. Neither are the special manifestations of wind action, such as sand dunes and dust storms, strictly confined to deserts, though most frequent therein.

It should be noted that the wind is not subject to the factors which limit the action of water, as discussed in the last chapter (p. 18). The wind does not move (that is, not directly) under the action of gravitation, and therefore it may, and does, move either up or down hill, carrying its load with it. The preponderance of translocation is naturally from higher to lower levels, but there is much in the opposite direction.[b] In area of attack the wind is complementary to water. It works on the areas upon which water does not, for water-covered areas are naturally not exposed to the wind. And since the areas covered by water are enormously less than those not so covered,[c] the wind has greatly the advantage. With regard to areas of deposition, the wind has no limits whatever. It can deposit anywhere. Then, too, the wind is constantly active, or nearly so, and thereby avoids the intermittence which is characteristic of much water action.

But if the wind escapes the limitations which are forced on water translocation, it has no less serious ones of its own. On account of the greater tenuity of air, the atmosphere has a specific transporting power much less than that possessed by water, and is much more closely limited in the size and weight of particles which it can handle. Further, a surface is much more easily protected from the wind than from the action of running water. Vegetation or surface moisture

[a] See, however, authorities cited on pp. 105–107.

[b] Cf. W. M. Davis—Jour. geol. 13: 384 (1905); Penck—Amer. jour. sci. (4) 19: 167 (1905).

[c] Areas covered by oceans and permanent lakes are, of course, excluded from consideration.

will prevent wind erosion much more completely than they will erosion by water.

The erosive and translocating activity of either wind or water is determined by a balance of various factors, some of which are favoring and some opposing, and the actual activity in any individual case will depend on the relative values of these factors. Those favorable to wind erosion are not always the same as those favorable to erosion by water, and consequently what increases wind action may decrease water action, and vice versa, and whether wind or water is most active in any particular region depends again on a balance of the factors. In an arid region wind has the advantage; in certain other places water action becomes much more important; while in still others, as, e. g., on rocky mountain slopes, both agents are perhaps equally active.

In order to show clearly the importance of wind action on soils, it is necessary to discuss the manner and manifestations of its action in more detail, paying particular attention to the importance of constant drift of soil, as mentioned above, but not neglecting the more unusual phenomena of dunes, sand storms, etc. These need discussion not only for the sake of completeness and on account of their occasional agricultural importance, but also because in them the phenomena are usually simple and apparent, and are consequently easier of examination and interpretation.

THE MECHANICS OF WIND TRANSLOCATION.

In order to be transported by the wind, material must first be lifted from the surface, and any discussion of the mechanics of wind translocation must therefore be prefaced by some consideration of the means by which the air currents attack the surface and acquire their load of detrital material. Loose dust and sand can be directly attacked by the wind, but rocks and other more or less indurated materials must first be disintegrated or abraded. This disintegration is largely performed by the general weathering agents, and the wind is usually an agent of removal rather than an agent of attack; but under certain conditions it is possible for the wind to attack and wear away even the hardest rocks, and this process may conveniently be called corrasion—the word employed by Powell [a] to designate the similar action of flowing water loaded with detritus in mechanically attacking the material over which it flows.

WIND CORRASION—SAND-BLAST ACTION.

The corrasive power of the wind is due altogether to the dust and sand which it carries, acting in the same manner as the well-known

[a] Science **12**: 229–233 (1888). The term has already been applied to eolian action by Passarge (Naturw. Wochens. **16**: 371 [1901]) and others.

sand blast much employed as a cutting and polishing agent. Rock corrasion by natural sand blast was first geologically described from the San Bernardino Pass, California, by Blake[a] in 1855. It has been many times observed in deserts, on seacoasts, and in all localities where drifting sand is common.[b] General discussions of the phenomena have been published by Gilbert,[c] Obruchev,[d] Walther,[e]

[a] Proc. Amer. assoc. adv. sci. **9**: 216–220 (1855), Amer. jour. sci. (2) **20**: 178–181 (1855), and Pacific Railway Repts., vol. **5**, p.92 (1856). The process had been earlier noted in brief by several desert travelers, especially Wellsted (loc. cit., in note *b* below).

[b] See Wellsted—Travels in Arabia, vol. **2**, p. 33–34, 204 (1838); Newberry—Geology of the Ives Expedition, pp. 17, 24 (1861); Fraas—Aus dem Orient, p. 200 (1867); Stowe—Trans. New Zealand inst. **5**: 105–106 (1873); Naumann—Neues Jahrb. Min. **1874**: 337–361; Heim—ibid. **1874**: 953–959; Kayser—Zs. deut. geol. Ges. **27**: 966 (1875); Ramsay—Quart. jour. Geol. soc. **34**: 87 (1878); Rohlfs—Libyschen Wüste, p. 59 (1875); Rolland—Rev. sci. (3) **1**: 611 (1881); Weisgerber—Rev. archéol. **2**: 4 (1881); Mickwitz—Neues Jahrb. Min. **1885**, II: 177; Narrative "*Challenger*" Expedition, vol. **1**, p. 373 (1885); De Geer—Geol. fören. förh. **8**: 501–513 (1886); Bajolle—Le Sahara de Ouargla, p. 16 (1887); Hettner—Gebirgsbau und Oberflächengestaltung der Sächsischen Schweiz, p. 292 (1887); Stapff—Verh. Ges. Erdk. Berlin **14**: 48–49 (1887); Jäkel—Zs. deut. geol. Ges. **39**: 287 (1887); Oldham—Rec. Geol. surv. India **21**: 159 (1888); Contejean—Compt. rend. **108**: 1208–1209 (1889); Choisy—Documents Mission Algérie, v. **1**, p. 327 (1890); Rolland—Géologie Sahara algérien, p. 215–217 (1890); Pechuel-Lösche—Ausland **65**: 446 (1892); Steenstrup—Geol. fören. förh. **14**: 493 (1892); Brackebusch—Peterm. Mitth. **39**: 156 (1893); Lóczy—Reise Grafen Béla Széchenyi, vol. **1**, pp. 507–508 (1893); Beck—Zs. deut. geol. Ges. **46**: 537–546 (1894); Goldschmidt—Tschermak's Min. Mitt. **14**: 131–141 (1894); Baltzer—Mitth. naturf. Ges. Bern **1895**: 28–29; Obruchev—Verh. Imp. min. Ges. St. Petersburg **33**: 249–255 (1895); Früh—Globus **67**: 117–120 (1895); Bain—Iowa Geol. surv. **8**: 337 (1897); Cornish—Geog. jour. **15**: 16 (1900); Walther—Wüstenbildung, p. 44, 51–52, 101 (1900); Beadnell—Compt. Rend. Cong. géol. intern. **8**: 857 (1900); Abel—Jahrb. geol. Reichsanst. **51**: 25–40 (1901); Futterer—Verh. Ges. deut. Naturf. Ärzte **73**, II 1: 227–229 (1901), Geog. Zs. **8**: 261–266, 335–338 (1902); La Touche—Mem. Geol. surv. Ind. **35**: 10–11 (1902); Passarge—Loc. cit. in *a*, p. 26; Brunhes—Compt. rend. **135**: 1133 (1902); Julien—Ann. N. Y. acad. sci. **14**: 152–153 (1902); Barron and Hume—Topography eastern desert of Egypt, p. 288–289 (1902); Russell—U. S. Geol. surv. Bull. **199**: 108, 122, 144 (1902); Johnsen—Centbl. Min. **1903**: 593–597, 662; Stein—Sand buried ruins of Khotan, pp. 307, 353, 368, 421, 430, 436 et al. (1903); Koken—Centbl. Min. **1903**: 625–628; A. P. Davis—U. S. Geol. surv. Water supp. pap. **73**: plate 5 (1903); Philippi—Zs. deut. geol. Ges. **56**: Monatsb. 64–67 (1904); Foureau—Documents scientifiques Mission saharienne, vol. **1**, p. 217–221 (1904); Ivchenko—Ann. géol. min. Russ. **7**, I: 57–58 (1904); **8**, I: 135–138 (1906); Lomas—Proc. Liverpool geol. soc. **10**: 192 (1905–6); J. Ball—Aswan Cataract, p. 112 (1907); Barron—Topography Western Sinai, p. 158, 216 (1907); Ferrar—Rept. Nat. Antarctic Exped. 1901–4, Nat. Hist. **1**: 87–89 (1907); Barron—Topography between Cairo and Suez, p. 61, 116–117 (1907); Cross—Bull. Geol. soc. Amer. **19**: 53–62 (1908); Hume—Cairo sci. jour. **2**: 318 (1908); Werth—Deut. süd-polar Expedition 1901–3, vol. **2**, p. 168–169 (1908); Gibson—Brit. assoc. Geol. photos. (2) No. 2879, desc. p. 10.

[c] Proc. Amer. assoc. adv. sci. **23**, II: 26–29 (1874); Amer. jour. sci. (3) **9**: 151–152 (1875).

[d] Loc. cit.

[e] Einleitung in der Geologie als historische Wissenschaft, p. 589–592 (1894).

Passarge,[a] and Brunhes.[b] Chatley[c] discusses briefly the mechanics of the phenomena. Rocks which have been subjected to wind corrasion usually have a smooth and highly polished though frequently irregular surface, sometimes with projecting crystals and ridges of the harder minerals, or with cavities (like pot holes) where softer parts have been worn away.[d] Blown sand is supposed also to be responsible for the faceted pebbles frequently found in deserts, on glacial sand plains, or on other sandy and wind-swept areas.[e]

[a] Naturw. Wochens. **16**: 369–373 (1901).

[b] Mem. Accad. Nuovi Lincei (5) **21**: 136–148 (1903).

[c] The force of the wind, p. 77–80 (1909).

[d] These corrasion forms are sometimes simulated by atmospheric (chemical) decay. See Choffat—Comm. Direcção trab. geol. Portugal **3**: 17–22 (1895–6); Ivchenko—Ann. géol. min. Russie **7**, I: 216–217 (1904); Tuckett—Geol. mag. (5) **1**: 12–13 (1904); Lake—Ibid., p. 89; Bonney—Ibid., p. 388–392; Baron—Ibid., (5) **2**: 17 (1905).

[e] It was once supposed by many geologists that these pebbles had been formed by the mutual attrition of stones in the beds of the glacial torrents. For this opinion see Braun—Verh. Berliner Ges. Anthrop. **1870–71**: 103; Meyn—Zs. deut. geol. Ges. **24**: 414 (1872); Keilhack—Jahrb. K. preuss. geol. Landesanst. **1883**: 173, **1884**: 210–238; Berendt—Ibid., **1884**: 201; Wahnschaffe—Zs. deut. geol. Ges. **36**: 411 (1884); Theile—Sitzungsb. Isis Dresden **1885**: 35–36. The now universal opinion is that they are formed by sand-blast corrasion, though the initial form of the pebble may have much to do with its final one. There exists a kind of faceted or planed bowlders and pebbles of undoubted glacial origin, but these have only a very superficial resemblance to the ordinary faceted pebbles or *Drei-Kanter*. The facets on these glacial pebbles are produced by ice planation while the pebble is fixed in the bed over which the ice is passing and which it is planing down. See Blanford—Rept. Brit. Assoc. Adv. Sci. **1886**: 630–631; Wynne—Ibid., pp. 631–632; I. C. Russell—Bull. Geol. soc. Amer. **1**: 120 (1890); Koken and Noetling—Centbl. Min. **1903**: 97–103; Koken—Ibid., p. 625–628; Philippi—Ibid., **1904**: 737–738, **1905**: 655, and Neues Jahrb. Min., **1906**, I: 71–80, and others in bibliography.

For descriptions of occurrences of faceted pebbles and discussions of their eolian origin, see the works cited in the bibliography under the following authors: Abel, E. W. Andrews, Barron (Topography between Cairo and Suez, p. 116–117), Bather, Beasley, Berendt, Bergt, Brackebusch (p. 156), W. D. Brown, Cadell, van Calker, van Calker and Tenne, Cazalis de Fondouce, Dames, Dawkins, Enys, Fegræus, Ferrar, Fontannes, Futterer (Geog. Zs. **8**: 335–338 [1902]), Gagel, Geinitz, Geiseler, George, Goebel, Goldschmidt, Gottsche (Sedimentär-Geschiebe Schleswig-Holstein, p. 6), J. W. Gregory (Dead Heart of Australia, p. 26), Gutbier, Harlé, Hedström, Heim, Högbom, Huntington (Pulse of Asia, p. 148), Kayser, Klemm (Erl. sp. K., p. 19–20), P. G. Krause, Laufer, Lenz (Timbouctou, vol **2**, p. 384), Lisbôa, Mackie, Marés, Meyn (Abh. geol. Spec. Karte Preuss. **1**: 652, 666, 686), Mickwitz, Milthers, Mügge, Nathorst, Papp, Prestwich (Geology, vol. **1**, p. 145), Preussner, Adolf Sauer, Sauer and Chelius, Steenstrup, Steinmann, Stone, Suess, Thomson, Travers, Tutkovskîĭ, Verworn, Virchow, Vorwerg, Wagner, Wahnschaffe, Walther, Wilmer, Wiman, Wittich, Woldřich, and Woodworth. See also Abel, Baltzer, De Geer, Jäkel, Johnsen, Koken, Mickwitz, and Steenstrup; loci citati in note *b*, p. 25. Gutbier's articles are the first notices of occurrences and those of Travers and of Enys contain the first suggestions of eolian origin. Mügge and Milthers give good résumés of present knowledge. Occurrences in the western United States are described by Blake (loc. cit., note *a*, p. 25), Gilbert (loc. cit., note *c*, p. 25), and George (loc. cit. in bibliography). Occurrences in New England are described in the articles by Stone and Woodworth, cited in the bibliography. The latter gives references to earlier New England literature.

Experiments on the geologic action of the sand blast have been published by Egleston,[a] De Geer,[b] Preussner,[c] Thoulet,[d] Harlé,[e] Hedström,[f] and W. D. Brown.[g]

Materials other than rocks are also frequently attacked by blown sand. Trees and plants are injured,[h] wooden structures abraded,[i] exposed glass articles etched,[j] etc. The telegraph wire along the Trans-Caspian Railway had to be removed after eleven years because in that time its diameter had diminished one-half because of sand blast corrasion.[k] The erosion of the wooden telegraph poles of the Southern Pacific Railway through the San Bernardino Pass in southern California is so great that the railway has been forced to protect them by piles of rock or by short supplementary posts placed on the windward side where they will take the corrasion and save the main poles.[l] Egleston describes the injury to building stones by blown sand and notes the gradual effacement of city tombstone inscriptions by dust blown from the street.[m] Blown snow crystals have a corrasive action similar to that of sand but less violent.[n]

However, the amount of débris derived from the sand blast corrasion of the rocks is not large, and is unimportant both to geology and to agriculture. The material moved by the wind comes mainly

[a] Trans. Amer. soc. civ. engs. **15**: 655 (1886).

[b] Geol. fören. förh. **8**: 501–513 (1886).

[c] Zs. deut. geol. Ges. **39**: 502 (1887).

[d] Compt. rend. **104**: 381–383 (1887); Ann. mines (8) **11**: 199–224 (1887).

[e] Bull. Soc. géol. France (3) **28**: 70 (1900).

[f] Geol. fören. förh. **18**: 601 (1896), **25**: 413–420 (1903).

[g] Proc. Liverpool geol. soc. **10**: 128–131 (1905–6).

[h] See p. 164 et seq.

[i] Reade—Geol. mag. (4) **8**: 193–194 (1901).

[j] Beck—Zs. deut. geol. Ges. **46**: 540 (1894); Sokolov—Die Dünen, p. 6 (1894). Merrill (Eng. mag. **2**: 605 [1892]) mentions a window pane from one of the Cape Cod light-houses which had its transparency destroyed by sand blast during a single storm.

[k] Walther—Wüstenbildung, p. 52 (1900).

[l] For photographs and descriptions of sand-blast action in this area (where it is probably more active than anywhere else in the United States) see Mendenhall—U. S. Geol. surv. Water supp. pap. **225**: 26 (1909).

[m] Trans. Amer. soc. civ. engs. **15**: 654–658 (1886). Futterer has noticed the corrasion of building stones in Heidelberg Castle—Mitth. Badischen Landesanst. **3**: 471–496 (1897). For notices of the injury of Egyptian monuments see Petrie—Proc. Roy. geog. soc. **11**: 648 (1889); Bolton—Trans. N. Y. acad. sci. **9**: 120 (1890); Walther—Einleitung in der Geologie als historische Wissenschaft, p. 591 (1894); Lomas—Proc. Liverpool geol. soc. **10**: 192 (1905–6). On the effects of corrasion on the ruins of the ancient cities of east Turkestan see Hedin—Through Asia, vol. **2**, p. 780 (1899); Stein—Sand buried ruins of Khotan, p. 368 et al. (1903), Ancient Khotan, p. 107, 243, 327, 328 et al. (1907), and Geog. jour. **34**: 16, 17, 21, 27, 35 (1909).

[n] Clarence King—Exploration of the Fortieth Parallel, vol **1**, p. 527 (1878); Davison—Quart. jour. Geol. soc. **50**: 478–479 (1894) and authorities there cited; Baltzer—Mitth. naturf. Ges. Bern **1895**: 35; Svenonius—Geol. fören. förh. **21**: 569 (1899); Tschirwinsky—Zs. Gletscherk. **2**: 111–112 (1907); Ferrar—Nat. Antarctic Exped. 1901–4, Nat. hist. **1**: 89 (1907).

from that already loosened and disintegrated by the general weathering agents. Exposed deposits of such material are rapidly attacked, the detached and blown grains acting as tools to loosen and remove further material. The soil is of course easily attacked in this way and is saved from complete removal only by the existence of certain agencies which tend to protect it.

PROTECTIONS AGAINST EROSION BY WIND.

The chief of these natural protectors are vegetation and surface moisture, and nearly all lands share to some degree in the benefits they afford, though in few is the protection perfect enough entirely to prevent attack. The protective action of vegetation is due to its preventing the contact of moving air with the soil surface. The air in the layer next the ground is entangled in the stalks and leaves of the plants and either its motion is entirely prevented or its velocity is greatly reduced. To act in this way the plants must of course be more or less closely matted, and isolated individuals are comparatively useless, as the wind is able to reach the soil between them with little or no loss of velocity. That form of vegetation is most efficient which provides (1) plants spaced most closely and (2) plants reaching highest into the air. Thus grasses and trees are found in practice to offer the best protection—the first because of the production of a close mat near the ground, and the second because of the height they attain. The real criterion of the protective action of any particular form of vegetation is naturally the ratio of the average height of the plants to the average distance between them. The greater this ratio, the greater the protection.[a]

The protective action of vegetation is not, however, entirely due to the reduction of the wind velocity at the surface, for the roots of the plants also act as binders in holding the soil grains together and preventing erosion either by wind or water. Possibly much of the efficiency of the grasses in preventing erosion is due to the extensive interlaced root system which is developed near the surface. The layer of decaying vegetable matter which accumulates under an established vegetation is also an opponent of wind action. It is usually pretty well held together by undecomposed stalks and branches and acts as a felted covering which is not readily broken by the wind. Its efficiency is, however, largely due to the fact that it tends to remain moist, for if its moisture be lost, much of the resistance to erosion is lost also, and the individual leaves, etc., are soon blown away. The vegetable matter in the soil itself (humus) is not unimportant in enabling resistance to the wind because of its tendency

[a] The shape of the plant will of course have some influence on the effective distance between plants. For instance, a low bushy species will furnish more protection than a tall one with a single stem, though the distance between plants be the same in each case.

to conserve moisture, and also to supply agglutinant materials which stick together the grains of the soil and help maintain its coherence.

The actual efficiency of any particular vegetal cover in preventing wind erosion is rather difficult to estimate. It is probable that sod and full-grown forests give nearly perfect protection, though even in this case some wind action occurs when the soil is accidentally exposed through the uprooting of a tree[a] or brought to the surface by earthworms or burrowing animals. The other forms of vegetation decrease more and more in efficiency with decrease in the ratio of plant height to plant distance. At the lower end of the series stand the plants common in semiarid regions which grow singly or in isolated clumps, and whose action in preventing wind erosion is very slight. Whether the natural vegetation of any piece of land will prevent its being acted upon by the wind depends largely on its water supply. If the land be kept sufficiently moist the vegetation is usually thick enough and high enough to form a more or less perfect protection, while an arid soil has practically no vegetation and therefore no protection. All gradations between these two extremes are possible and are found in nature.

The vegetal covering of cultivated fields (excepting pastures) is seldom such as to furnish a sufficiently complete protection. Cultivated plants are usually spaced much more widely than wild ones and in many cases a large part of the area of the field is entirely bare of vegetation. These spaces between plants and between rows of plants are easily attacked by the wind, but more important is the fact that cultivated fields are during a part of each year bare of any vegetation whatever. The operations of plowing, harrowing, etc., have for their main objects the destruction of the natural vegetation (weeds) and the loosening of the soil. In both ways wind erosion is assisted and it is therefore apparent that cultivation will, other things equal, tend to increase the amount of soil moved by the wind, so much so in some cases that the clearing of the natural vegetation preparatory to cultivation has led to serious loss of soil by blowing.[b]

The second great protection against wind erosion is a moist condition of the surface. The presence of films of moisture between the soil particles sets up forces due to surface tension. These forces tend to hold the particles together.[c] If, therefore, the surface of the soil be moist there will exist a force strongly opposing the action of the wind in detaching soil particles and in many cases competent entirely to prevent attack.[d] It is seldom, however, that the actual surface is moist. There are usually a few grains which are dry enough to lack the surrounding water films. These are blown

[a] See Shaler—Ann. Rept. U. S. Geol. surv. 12: 273–274 (1892).

[b] See pp. 164–172 below.

[c] See Bull. 10, Bur. of Soils, and Bull. 50, ditto, pp. 49–51.

[d] See e. g. the experiments of Hensele—Forsch. Geb. agric. Phys. 16: 363 (1893).

away, exposing the grains below, which are dried by the wind and themselves blown away, enabling the wind gradually to work its way even into a soil which is comparatively wet.[a] In order that there may be a complete protection against wind action it is necessary that moisture be supplied from below by capillary rise as rapidly as it is removed on the surface by evaporation.[b] A soil may be quite moist and still be subject to wind action owing to the presence of a very thin dry layer on the surface which is renewed as rapidly as it is removed.[c]

This drying effect of the wind and consequent blowing of even wet soil is well illustrated by phenomena observed on the sandy soils of Anne Arundel County, Md. These soils blow a great deal at all times, and especially when freshly plowed, but contrary to what might be expected they blow more when plowed wet than when plowed dry. The fact that some blowing takes place on the wet soil is not difficult to understand. Owing to the sandy character of the soil, as shown by the mechanical analysis given in Table I, it is very permeable and well drained and the rain water, though rapidly absorbed, is as rapidly drained away to lower levels, leaving in the surface layers only that water which is held by capillary and hygroscopic action in the films about the grains.

TABLE I.—*Mechanical analysis of soil from Severn, Anne Arundel County, Md., which is much subject to blowing.*

Grade.	Size.	Name.	Per cent.	Grade.	Size.	Name.	Per cent.
	Mm.				*Mm.*		
1.....	2 –1	Fine gravel.....	0.2	5.....	0. 1–0.05	Very fine sand....	1.5
2.....	1 – .5	Coarse sand.....	24.4	6.....	.05– .005	Silt.....	2.3
3.....	.5 – .25	Medium sand.....	55.4	7.....	Below .005	Clay.....	1.1
4.....	.25– .1	Fine sand.....	15.4				

It is apparent from surface tension relations[d] that the capillary films on the large particles of a sandy soil are more easily broken than those on the fine particles of a clayey soil, i. e., a sandy soil loses its capillary moisture more rapidly, and is more rapidly dried out (on the surface) by the wind. For this reason a sandy soil always tends to blow more when wet than does a soil composed of finer particles, and consequently is less protected by moisture than is a loam or

[a] This action has been noticed by Bernard in the Sahara—Compt. rend. Soc. géog. **1890**: 323. Another illustration is the observation that the sand of the Cape Town (South Africa) dunes blows badly when the wind is dry but hardly at all when it is wet, Braine—Proc. Inst. civ. engs. **150**: 388 (1902). Cf. also note *a*, on page 58 below.

[b] On evaporation from soils and consequent capillary rise, see Bull. **38**, Bureau of Soils, pp. 18–24 (1907).

[c] That the wind can attack the soil to a considerable degree in a climate which is not perfectly arid has been noted by Willis in China (Carnegie Institution of Washington Pub. **54**: 247 [1907]). See also the instances of damage by soil blowing cited on pp. 164–167 below.

[d] See Bull. **10**, Bureau of Soils.

clay. Clay soils in particular hold on to their moisture so tenaciously that they blow practically not at all when wet.

That more blowing should be observed on the freshly plowed soil when moist than when dry is more difficult of explanation, but is probably due to a looser texture in the moist soil. It has been shown by Cameron and Gallagher[a] that the structure of a soil is dependent on its water content and that for each soil there is a certain "critical moisture content" which corresponds to the maximum of flocculation and looseness of texture. This critical moisture content is also that content at which water is most strongly held (mechanically) by the soil. Amounts of water above this content can be drained away quite readily, whereas below this point very little water can be mechanically removed, even by centrifuging at very high speeds.[b] On account of the exceptionally good drainage of the soils under consideration their water content when wet would probably be not much greater than the critical moisture content, as water in excess of this quantity would flow to lower levels. Hence the wet soil when stirred by plowing would take on the maximum openness of structure of which it was capable and would be most easily dried out superficially and blown away by the wind. The dry soil, on the other hand, when stirred by plowing would tend to pack more closely together and would hence be less open to attack. These phenomena are in accord with the observation of Wesseley[c] that dune sands are looser after having been moistened.

In deserts where there can be no protection by either vegetation or moisture another protective agent is developed—the "desert pavement," recently well described by Tolman.[d] When loose mate-

[a] Bull. 50, Bureau of Soils.

[b] Bull. 45, Bureau of Soils. The "critical moisture content" of Bulletin 50 and the "moisture equivalent" of Bulletin 45 mean the same thing (see Bull. 50, pp. 54–55). This same moisture content is identical with the so-called "optimum water content" for the growth of plants (see Bull. 50, p. 57 et seq.).

[c] Flugsand, p. 62 (1873).

[d] Jour. geol. 17: 149–151 (1909). For the ideas expressed in this paragraph I am largely indebted to suggestions received from Professor Tolman's papers and from him personally.

The surface concentration of stones and pebbles in desert regions had previously been observed by Blake—Rept. Pacific Rwy. Surv., vol. 5, p. 230 (1856); Bradley—Ann. Rept. U. S. Geol. and Geog. Surv. Terr. 6: 211–212 (1873); Wesseley—Flugsand, p. 50, 64 (1873); Gilbert—Rept. Wheeler Surv., vol. 3, p. 82 (1875); Tenison-Woods—Jour. and Proc. Roy. soc. N. S. Wales 16: 84–85 (1882); Sokolov—Die Dünen, p. 12 note (1894); Walther—Wüstenbildung, chap. 9 (1900); Cholnoky—Földtani Közlöny 32: 136 (1902); Lomas—Trans. Liverpool geol. soc. 10: 190 (1905–6); Gregory—The dead heart of Australia, p. 70 (1906); Ferrar—Rept. Brit. Assoc. Adv. Sci. 1907: 504–505; Hume—Cairo sci. jour. 2: 318 (1908); and others. Its protective action seems, however, to have been first noted by Tolman (loc. cit.).

Of interest in this connection is the fact that the surface layers of desert sand are apt to be coarser than those below—an observation made in Sinai by Bolton (Trans. New York acad. sci. 9: 119 [1890]), and in Egypt by Cornish (Geog. jour. 15: 12 [1900]) and confirmed by the present writer at many places in the deserts of North America.

rial containing pebbles or larger stones (e. g., ordinary mountain wash) is exposed to wind action the finer dust and sand are blown away and the pebbles gradually accumulate on the surface, forming a sort of mosaic which protects the finer material underneath from attack. This is the "desert pavement," a good example of which is shown in Plate I, figure 1. It is obvious that a pavement will be formed as soon as the wind has worked through a layer of heterogeneous material sufficiently thick to contain one layer of pebbles; the actual thickness depending upon the proportion of pebbles in the deposit. This thickness will therefore form the practical limit to the wind erosion of that deposit, and in the heterogeneous deposits of ordinary deserts this limiting thickness will be comparatively small. It is, of course, true that the desert pavement is not absolutely permanent. Its pebbles will yield slowly to corrasion and occasionally to fracture by temperature change,[a] and loose material may be removed from underneath them during the rare periods of flowing water, or by the "creep" of soil. The susceptibility of the pavement pebbles to removal and change is shown by the rarity of perfect pavements. There is almost always some uncovered space between the individual pebbles and there are frequently bare spots in which the pebbles are spaced more widely. Of many pavements examined by the writer only two[b] have at all closely approached perfection. This lack of perfection is, however, but a minor matter. Even though it be far from a perfect one, a desert pavement is a most effective protection to fine material beneath, and it is certain that the formation of such pavements is a phenomenon of constant occurrence wherever heterogeneous material is exposed to wind attack,[c] and of far-reaching importance in limiting the eolian degradation of desert surfaces.

[a] The writer has seen and collected such fractured pebbles on the Colorado Desert northeast of Superstition Mountain. They are, however, comparatively rare. For another occurrence, see Högbom—Geol. fören. förh. **16**: 387–390 (1894).

[b] A pebble pavement at Knob Station on the Southern Pacific Railway in the Colorado Desert, California, and a small pavement of tufa fragments on the north slope of Rattlesnake Butte, near Fallon, Nev. (This is the one shown in Pl. I, fig. 1.) Professor Tolman tells me that there is an extensive and still more perfect pavement north of the Chocolate Mountains, California.

[c] The surface concentration of the larger fragments in heterogeneous deposits subjected to wind erosion is not confined to deserts. "Desert pavements" in coastal dune areas have been described by Richardson (Rept. Yorkshire phil. soc. **1902**: 47) and Oldham (Mem. Geol. surv. India **34**: 141 [1903]), and the writer has seen typical examples on the dune lands of New Jersey and of the southern California coast, and on the great dune area south of the Arkansas River in eastern Colorado and western Kansas. There is a similar pavement of shell fragments covering a small area on Monterey Peninsula, California, though here the possible action of man, birds, or other animals can not be certainly excluded. Neither is it certain that the desert pavement is always or exclusively the product of wind action. It is very probable that under proper conditions flowing water can produce a practically identical formation. The writer has examined pavements west of Hazen, Nev., which he believes to be of this class. Cf. also Chelius and Vogel—Neues Jahrb. Min. **1891, I**: 104.

FIG. 1.—DESERT PAVEMENT OF TUFA FRAGMENTS NEAR FALLON, NEV.

FIG. 2.—TYPICAL CRESCENTIC DUNE IN THE DELTA OF CARRIZO CREEK, COLORADO DESERT (CALIFORNIA).

FIG. 1.—REMOVAL OF SOIL FROM AROUND TREE.

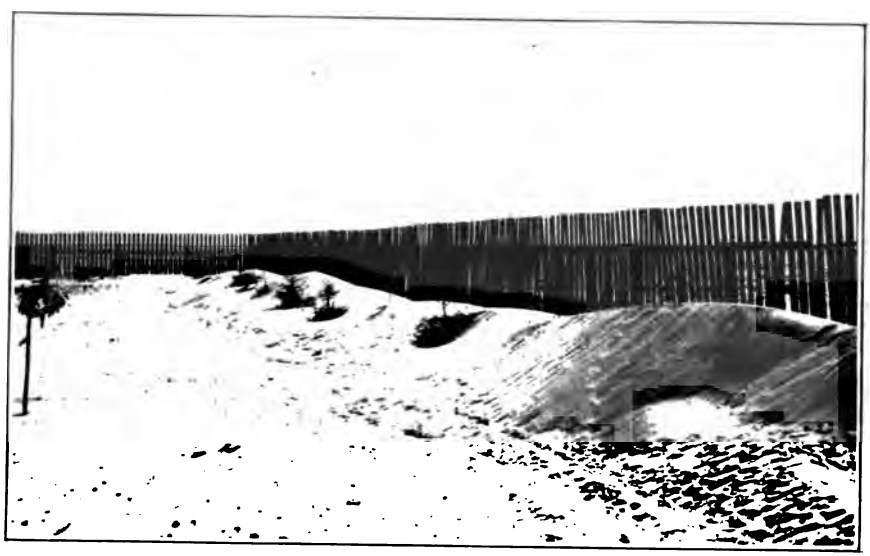

FIG. 2.—BLOWN SAND COLLECTED BEHIND FENCE.

In addition to these pavements, there are two other protections against wind action which are of some importance in deserts; first, the salt crusts, which, possessing more cohesion, are less easily attacked than is the naked soil; and second, the surficial crusting and baking not only of clays and loams but of fairly sandy soils as well, the nature of which is not yet well understood, but the occurrence of which is familiar to all who have been much in desert countries.[a] The more complete discussion of these phenomena, while not lacking in interest, would lead too far afield.

THE LIFTING OF EXPOSED MATERIAL.

The lifting of loose material lying exposed on the surface is largely the work of eddies and irregularities of movement in the wind. In the earlier discussions of fluid friction the moving fluid was considered as flowing past the stationary surface with no deformation of its lines of flow, and all friction was assumed to take place at the solid-fluid surface ("skin friction") or else between layers of fluid parallel to that surface. The very thin layer immediately next the surface was assumed stationary or moving with a very low velocity. The next layer moves a little faster, the next a little faster still, etc., but all maintain their identity and there is no mixing of the layers. Did this sort of thing actually occur in flowing fluids there would be practically no lifting of material into the current. The lower layer might become somewhat charged with suspended material but practically none would be able to rise to layers above. In nature, however, this simple laminated flow does not exist. Whatever may be the true motion of flowing fluids it is undoubtedly very complex and there is much mixing of the hypothetical layers of flow. McGee[b] has recently elaborated a hypothesis with regard to flowing water which considers the fluid made up of discrete particles or "modules" which move by "saltation" in a series of leaps, describing paths which probably approach the parabola. If water flows in this way it is easy to see how material can be picked up from the bottom and carried along, the solid particles moving (as is known to be a fact) in a saltatory manner similar to that ascribed to the hypothetical water module. In any event it is certain that water flow is not laminar and that there are innumerable eddies and cross-currents which thoroughly mix the body of a stream and enable material to be lifted from the bottom and carried along in suspension and in saltation.

[a] An extreme case is the protection by the calcareous cementation of the soil particles into aggregates and layers as noticed by Russell on the Snake River plains in Idaho. (U. S. Geol. surv. Bull. 199: 143 [1902]).

[b] Bull. Geol. soc. Amer. 19: 193–220 (1908).

Whether the phenomena of flowing water and of flowing air are perfectly analogous is perhaps open to question, and at any rate the air currents with which we are familiar are really but eddies in the bottom of an ocean of air and hardly comparable with currents in limited and confined masses of water like streams. It is, however, certain, as has been shown by Langley,[a] that the air currents are exceedingly variable and made up of many conflicting cross currents and eddies, and the hypothesis of laminar flow is just as inapplicable to air as to water. The wind is made up of many momentary currents blowing upward and downward[b] as well as horizontally, and what we call the "wind direction" is the resultant of these momentarily variable directions and denotes the direction in which the whole mass of air is moving rather than the direction of motion at any particular place and particular instant. It is no matter whether these cross currents and eddies be considered a characteristic concomitant of moving air (as seems probable) or whether they be deemed accidental variations due to the interference of terrestrial obstacles. The fact remains that they exist and are of great importance in promoting the thorough mixing of the atmosphere and enabling it to lift fine material from the surface of the ground. The actual form of the eddies is unknown and is probably variable. Whirling eddies are known to be efficient, but dust can probably be lifted in many other ways.

The preceding discussion relates to the way in which surface deposits are attacked and the material made available for the transporting activity of the wind. The lifting of the finer material higher into the atmosphere is accomplished in the same general way. The atmosphere is in such general and constant circulation, vertical as well as horizontal, that material fine enough to remain in suspension for any appreciable time can be carried far above the surface simply by the normal movement of the air currents. Material is also lifted by whirlwinds as described on pages 83–88 and very fine dust is carried up by the rising of masses of air under changes of temperature—the ordinary convectional circulation of the atmosphere.[c]

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[a] "The Internal Work of the Wind," Smithsonian Contrib. **27**, No. 884 (1893); Amer. jour. sci. (3) **47**: 41–63 (1894).

[b] On the vertical component of the wind velocity see Abbe—Monthly weath. rev., **31**: 536–537 (1903); Dechevrens (with notes by Abbe and by Marvin)—ibid. **32**: 118–121 (1904).

[c] On the presence and nature of vertical currents due to this cause see Schreiber—Abh. K. Sächs. met. Inst. **3**: 18–24 (1898); Exner—Sitzungsb. Kaiserl. Akad. Wiss. Vienna, Abt. IIa, **112**: 345–369 (1903); Besson—Met. Zs. **20**: 398–409 (1903); Elias—Illus. aeron. Mitth. **8**: 394–396 (1904); Hoffman—Beiträge Geophysik **6**: 543–559 (1904); Conrad—Met. Zs. **22**: 266–267 (1905); Clayton—Mon. weath. rev. **33**: 390–391 (1905).

THE SORTING OF MATERIAL BY THE WIND.

Of course under equivalent conditions the smaller particles are more easily moved by the wind, and consequently in attacking a heterogeneous deposit the wind tends to make a selection, removing the finer particles and leaving the coarser behind.[a] Professor Udden in his excellent monograph[b] on this subject classifies wind deposits as (1) lag gravels, which represent the coarse residuum from which all finer material has been blown away; (2) drifting sands, which can be readily moved along the surface but not lifted to any height; (3) fine sands found in the lee of dunes ("lee sands"); and (4) dust, which settles out slowly and may be carried considerable distances. There is no sharp separation between these various classes, and each grades into the next.

This sorting action of the wind depends not really on size but on the mutual relations of mass, surface area, and shape. The forces exerted by the wind against a suspended particle are due to the impact of the air against the particle and to friction along its surface, which forces vary with the size and shape of the particle, while the only opposing force is that of gravity which varies with its mass. It is of course possible to consider the forces acting between the air and the particle as due entirely to impact; for, if gases be considered as composed of free moving particles, all manifestations of gaseous "friction" are really due to the impact of particles of gas against the solid surface. It is convenient, however, to make a rough distinction between the "impact" forces due to the momentum of the air which directly impinges on the body and the "frictional" forces due to secondary impact and connected with the viscosity of the air and similar effects. It is possible that this latter component may include effects other than purely mechanical impact, as perhaps electric or magnetic attractions, gravitational actions, etc.

The forces due to direct impact will vary (for any given wind velocity) with the cross section of the particle in the plane perpendicular to the wind direction and with the angle (or angles) which the exposed surface makes with this direction; therefore, practically with the cross section of the particle, its shape, and its orientation relative to the wind. The forces due to friction will vary with the area and configuration of the exposed surface. For particles of very irregular shape—as, for instance, mica flakes—these relations are far too complex for any analysis, except the general conclusion that ease of suspension will increase with increasing irregularity of shape, and of course with decrease of mass. However, for particles which

[a] Cf. the discussion of desert pavements on pp. 31–33 above.

[b] The mechanical composition of wind deposits, 1898.

approach the spherical form the relations are much simpler, and the ease of transport can be fairly well represented by the ratio of the surface area of the particle to its mass. With such regular particles decrease of size (represented by the diameter) means increase of this surface-mass ratio, and consequently small spherical particles are more easily carried than large ones. Thus since most of the soil particles, and especially those classed as sand, are likely to be approximately spherical, their ease of transport is roughly dependent upon their diameter, and they are sorted by the wind pretty closely according to this dimension. The more irregular particles are more easily carried and will be found among material which (if regular in shape) is of smaller linear dimensions. As a practical conclusion of general applicability it may be stated that the greater the surface-mass ratio of a particle the more easily will it be suspended.

All this assumes that the particles under consideration have the same specific gravity. If the specific gravities vary, either because of difference of material or of internal cavities or inclusions, that particle with the highest value will have the greatest mass per unit surface and will consequently tend to fall most rapidly. This is well illustrated by the fact that in showers of volcanic ash the heaviest minerals, as magnetite, augite, etc., fall nearest the volcano, as was observed for the Krakatoa eruption by Murray and Renard[a] and by Judd,[b] at Vesuvius by Matteuci,[c] at Santa María by Brauns,[d] and in dust from the recent West Indian eruptions by Schmelck.[e] Another interesting example of air elutriation according to specific gravity is the winnowing process employed to separate gold from alluvial gravels in Mexico,[f] Central Australia,[g] and Central Asia,[h] where water is too scarce to permit the employment of the ordinary processes.

The result of this air sorting of blown material is that practically all eolian deposits are remarkably uniform in grain, as has been pointed out by Udden.[i]

Dune sands in particular are very uniform because made up of material which can be drifted, but not raised, by the wind. Material a little coarser is not moved at all and forms lag gravels, while material a little finer is blown clear away. Indeed, the great uni-

[a] Nature **29**: 588 (1884).
[b] Roy. Soc. Rept. on Krakatoa, p. 39; and Nature **29**: 595 (1884).
[c] Boll. Soc. sism. ital. **6**: 207–312 (1901).
[d] Centbl. Min. **1903**: 290. Cf. Schottler—ibid., pp. 288–289.
[e] Chemztg. **27**: 34 (1903).
[f] Personal communication from W J McGee.
[g] Carnegie—Spinifex and sand, pp. 131–133 (1898).
[h] Huntington—Pulse of Asia, p. 197 (1907).
[i] Mechanical composition of wind deposits, pp. 60 et seq. (1898).

formity of eolian sands has been advocated by van den Broeck[a] and by Beck[b] as a means of distinguishing them from sands deposited by other means. Dust deposited from suspension in the air ("dust-falls," etc.), is also quite uniform,[c] and in the case of falls of volcanic dust the same is true of the material collected at any one place,[d] the fineness increasing with distance from the volcano.

DEFLATION.

The complete blowing away of fine dust, leaving sand and coarser material behind, is known as "deflation."[e] It is the eolian analogue of the removal of water-borne silt by the rivers. By its means only is the wind able to lower a surface on which it works. The finely disintegrated material is continually removed from the surface and the rocks and coarser fragments left exposed to the attack of the disintegrating and abrading agents.

It is because of this phase of wind action that the surfaces of deserts are so uniformly sandy or stony. Any dust which is produced by abrasion or other means (and there is a great deal) is at once blown away, leaving only the particles which are too coarse to be "deflated."[f] The phenomena are quite analogous to those concerned in the formation of the "desert pavements" above described. Rock disintegration (and especially the largely mechanical disintegration which obtains in deserts) leads to the production, progressively, of stones, gravel, sand, and dust. If the dust be blown away, sand is left, and if the sand be disintegrated or be itself drifted away, gravel or bare rock is left. Or, if the floor of the desert be formed of already disintegrated heterogeneous material, the finer part will be removed, and the resulting surface will be sandy, gravelly, or rock-strewn, depending upon the relative amounts of the materials of various fineness in the original deposit and upon their relative rates of disintegration or removal. Obviously the surface character of any par-

[a] Note in discussion of Briart—Bull. Soc. géol. France (3) 8: 587 (1880).

[b] Zs. deut. geol. Ges. 46: 539 (1894).

[c] See Herrmann—Annalen Hydrog. 31: 481 (1903).

[d] For an example from the West Indian fall of March 22, 1903 (at Barbados), see report of an examination made by Doctor Gottsche, of Hamburg, in Annalen Hydrog. 31: 270–271 (1903).

[e] The term is due to Walther (Wüstenbildung, chap. 9 [1900]). For a discussion of the advisability of employing it, see Passarge—Naturw. Wochens. 16: 372 (1901), and Walther, ibid., pp. 431–432. From philological considerations "efflation" would probably be better, but "deflation" has been so long and so generally used that it seems inadvisable to make the change.

[f] In the rare spots in which the desert surface is composed of clay or silt there is always protection by moisture, alkali, chemical cementation, surface crusting, or some similar agency. These spots are also usually places to which fine material is frequently supplied (usually by water action), as, for example, the playas.

ticular desert (excluding salt deserts) will depend upon the character of the materials originally present[a] or being supplied, and upon the relative rapidity with which they are disintegrated and removed. The presence or supply of much resistant gravel will cause the formation of a desert pavement (gravelly desert); the presence of much sand (either original or as the result of disintegration of weakly resistant gravel or rock) and the existence of conditions forbidding the escape of this sand by drifting along the surface, will cause a sandy desert, etc. Of course in the analysis of the origin of desert surfaces agents other than eolian must be assigned their share. The question is one of too great detail and complexity to be fully discussed here.

The process of eolian erosion and deflation of the débris has recently been suggested in explanation of the origin of the peculiar flat plains of the American deserts out of which rise isolated mountains or mountain ranges. It has always been believed that these plains were composed of immense thicknesses of rock débris rainwashed from the higher land. The original valleys had been filled up, leaving the higher mountains projecting as islands from a solid sea of mountain waste.[b] McGee,[c] however, in 1896 announced that at least a part of the plains of Sonora in northwestern Mexico were not deep deposits of disintegrated materials, but were rock floors comparatively thinly mantled with loose débris, and Keyes[d] in 1903 found the same to be true of certain of the plains of New Mexico and discovered that the underlying strata were not horizontal, but greatly inclined, the approximately horizontal surface being produced by the edgewise planing of these strata, evidently by some erosive agent. At the same time Passarge[e] in studying a similar, though geographically more mature, region in South Africa,

[a] At the inception of desert conditions.

[b] These conclusions follow from either the fold theory, or the faulted-block theory of Basin Range structure. On these theories and the structure of the valleys in general see Powell—Geology Uinta Mts., p. 29 (1876); Clarence King—Explor. Fortieth Parallel, vol. 1, p. 735 (1878); Dutton—Plateaus of Utah, p. 47 (1880); Gilbert—Surv. West of 100th Merid., Prog. Rept., p. 48–52 (1874); Russell—Ann. Rept. U. S. Geol. surv. **4**:443 (1884); and Monogr. **11**: 26 (1886); Diller—Bull. U. S. Geol. surv. **33**:15 (1886), and Bull. Phil. soc. Wash. **9**:4–5 (1887); Le Conte—Amer. jour. sci. (3) **38**:259 (1889); R. T. Hill—Topog. folio U. S. **3**:8 (1900); Spurr—Bull. Geol. soc. Amer. **12**:217–270 (1901); D. W. Johnson—Amer. geol. **31**:135–139 (1903); Davis—Science (n. s.) **14**:457 (1901), Bull. Mus. comp. zool. **42**:129–177 (1903), and ibid. **49**:17–56 (1905); M. R. Campbell—Bull. geol. soc. Amer. **14**:551–552 (1904); Keyes—Amer. geol. **33**:19–23 (1904); Herrick—ibid. pp. 376–381; Louderback—Bull. Geol. soc. Amer. **15**:343 (1904); Keyes—Jour. geol. **16**:434–451 (1908).

[c] McGee and Johnson—Nat. Geog. Mag. **7**:127 (1896); McGee—Bull. Geol. soc. Amer. **8**:90 (1897).

[d] Amer. Jour. Sci. (4) **15**:207–210 (1903); Amer. geol. **34**:160–164 (1904). His conclusions are more fully stated in his papers cited below.

[e] Zs. deut. geol. Ges. **56**, Monatsb.: 193–215 (1904); Naturw. Wochens. **19**:657–665 (1904); and his comprehensive monograph, Die Kalahari (1904).

had come to the conclusion that the agent of this planation was the wind [a] and that plains of this character with isolated steeply rising mountains ("Inselberge") must be regarded as plains of eolian erosion.

This conclusion has been accepted by Keyes [b] and Hill [c] as applying to the deserts of the southwestern United States, but it has not attained general acceptance and has been challenged in particular by Tolman [d] on the ground that it is only very rarely, if at all, that these desert plains (or "bolsons") are planed rock floors, but that in the vast majority of cases they are really valleys filled with débris washed from the mountains, and unconsolidated except for occasional layers cemented by lime carbonate (so-called "caliche"). Tolman's conclusions are supported by well logs for certain of the bolsons, and the writer has seen logs and other evidence which point the same way in the case of a few others. For these the hypothesis of eolian origin must be abandoned. This failure of the hypothesis to be everywhere applicable does not, however, entirely discredit it. Passarge's conclusions in the Kalahari have not been challenged, and it is quite possible that even in North America the same processes may have been determining in certain places, though in others they seem certainly to have played a minor rôle. The question is one which can be settled only after the acquiring of more exact and accurate knowledge of the underground conditions in the areas affected.

This controversy aside, there is little doubt of the reality of the process of eolian planation and of the activity of deflation as a general agent of removal. Its effects have been noted by Davis [e] on the South African veld, by Obruchev,[f] Berg,[g] and Ivchenko [h] in Russian central Asia, by La Touche [i] in India, by Blackwelder [j] in the Laramie Basin, Wyoming, and by Hundhausen [k] in southern France; and Davis [l] has pointed out its place in the arid-region geo-

[a] This conclusion is supported by Hecker—Zs. deut. geol. Ges. **57**, Monatsb.: 175–179 (1905).

[b] Bull. Geol. soc. Amer. **19**: 63–92 (1908); Proc. Iowa Acad. Sci. **15**: 137–141 (1908); Jour. geol. **17**: 31–37 (1909); Pop. sci. mon. **74**: 19–30 (1909).

[c] Eng. min. jour. **85**: 688 (1908).

[d] Jour. geol. **17**: 136–163 (1909). See also Tight—Amer. Geol. **36**: 271–284 (1905), who points out that the bolson plains are by no means all of the same character or genesis.

[e] Bull. Geol. Soc. Amer. **17**: 426, 435–444 (1906).

[f] Verh. Imp. min. Ges. St. Petersburg (2) **33**: 260–263 (1895).

[g] Pédologie **1902**: 37–44.

[h] Ann. géol. min. Russie **7**, I: 43–59 (1904); **8**, I: 135–197 (1906).

[i] Mem. Geol. Surv. India **35**: 10 (1902).

[j] Jour. geol. **17**: 429–444, esp. p. 443 (1909). See also Knight and Slosson—Wyo. agr. expt. stat. Bull. **49**: 88 (1901).

[k] Globus **90**: 46–48 (1906).

[l] Jour. geol. **13**: 381–407 (1905).

graphical cycle, and the possibility of the production by its means of plains of erosion which have no relation to sea level. Such plains have been discovered in eastern Egypt by Barron[a] who describes[b] an especially interesting occurrence of gentle slopes which simulate those due to dip of the strata but which are really of eolian origin. According to Petrie[c] at least 8 feet has been removed by deflation from part of the Nile Delta during the past 2,600 years. Crawford,[d] Gilbert,[e] Woodward,[f] and Coffey[g] have described the origin of surface depressions through wind removal, and Forbes[h] has noted the lowering of arid region cattle paths by wind erosion. Mention should also be made of the action of the prevailing wind in modifying the so-called law of von Baer relating to the asymmetric development of river valleys; which action includes not only direct erosion of the opposing bank, but also eolian deposition behind the windward bank, sidewise blowing of the waters of the river (with consequent asymmetric erosion), and the action of wind-driven rain.[i]

Since the wind has no base level of erosion as water has, it may seem that level plains could not be produced by wind action, but that the tendency would be to form hollows where the rock was softer and more easily disintegrated. This tendency is, however, counteracted by two others; first, the excess of corrasion to which elevated portions are exposed and which tends to wear them down to the common level;[j] and, second, the action of rain wash (sheetfloods) in carrying loose material into depressions and tending to fill them up.[k]

[a] Topography of Sinai, Western Portion, p. 17, 216 (1907).

[b] Topography between Cairo and Suez, p. 19, 115–116 (1907).

[c] Proc. Roy. geog. soc. **11**: 648 (1889).

[d] Trans. New Zealand inst. **12**: 415–416 (1880).

[e] Jour. geol. **3**: 47–49 (1895).

[f] Geol. mag. (4) **4**: 363–366 (1897).

[g] Jour. geol. **17**: 754–755 (1909).

[h] Ariz. agr. expt. stat. Bull. **38**: 249–255 (1901).

[i] On these various actions of the wind see Buff—Ann. Chem. Pharm. Supp. Bd. **4**: 223–224 (1865); von Vilovo—Mitt. geog. Ges. Vienna **24**: 179–187 (1881); Tietze—Verh. geol. Reichsanst. **1881**: 37–40, Jahrb. ditto **32**: 132–148 (1882); Zöppritz—Verh. deut. Geographentags **2**: 53 (1882); von Dunikowski—Zs. deut. geol. Ges. **36**: 65–66 (1884); Tietze—Jahrb. geol. Reichsanst. **37**: 825–830 (1887); Rucktäschel—Peterm. Mitt. **35**: 224–226 (1889); Klinge—Bot. Jahrb. **11**: 301–304 (1889); Köppen—Met. Zs. **7**: 34–35, 180–182 (1890); Zimmermann—Zs. deut. geol. Ges. **46**: 493–500 (1894); Penck—Morphologie der Erdoberfläche, vol. 1, p. 360–362 (1894); Girard—Compt. rend. Soc. géog. Paris **1897**: 273–275; Rutot—Bull. Soc. belg. géol. Mém. **17**: 95 (1903); Fabre—Géographie **8**: 291–316 (1903); and Rühl—Zs. Ges. Erdk. Berlin **1907**: 374–377. The results and interactions of the various factors have recently been well analyzed by Smolenski—Peterm. Mitt. **55**: 101–107 (1909).

[j] Petrie—Proc. Roy. geog. soc. **11**: 648 (1889); Brunhes—Mem. Accad. Nuovi Lincei **21**: 137 (1903); Stromer—Centbl. Min. **1903**: 4–5; Tolman—Jour. geol. **17**: 150 (1909).

[k] Passarge—Zs. deut. geol. Ges. **56**, Monatsb.: 208 (1904). On sheetflood action, see McGee—Bull. Geol. soc. Amer. **8**: 87–112 (1897). Tolman (loc. cit. p. 148) denies the reality of sheet-flood erosion, but the distributive action of such floods is unquestioned.

The result is that only the most resistant rocks are able to withstand the general tendency of planation, and these rocks form the elevated mesas and doubtless many of the islandlike mountains of the "Inselberge" regions, though some of the latter are perhaps the result of tectonic movements or remnants of an earlier topography. The absence of a limiting base level also, as noted by Penck,[a] permits the wind to carry its level of planation even below sea level, provided the waters be excluded by a bordering barrier. In fact this has possibly happened in the case of Death Valley in California and the Dead Sea Valley in Asia Minor. Keyes[b] has, however, pointed out that there is a natural lower limit of eolian erosion fixed by the position of the ground-water table, which in turn has usually some relation to the sea level.[c]

Deflation has been suggested by Walther[d] as a possible agent in the production of the great amphitheaters of the Canyon of the Colorado. Davis[e] rejects this hypothesis but it is favored by Cross[f] and by Tolman.[g]

The importance of deflation to the student of soils lies in the other aspect of the phenomena—the deposition of the deflated material. If large quantities of fine dust are deflated from desert regions they must be deposited somewhere, and at least a part of the deposition will be on land surfaces. Dust so deposited may have not only a geological but an agricultural importance. It will be shown later that a considerable quantity of dust blown from the Sahara has been deposited in Europe and that the process is still going on. Other regions show analogous phenomena.[h]

THE COMPETENCE[i] OF THE WIND.

The actual size of the particles which can be transported, and consequently the limiting sizes of lag gravel, drifting sand, etc., in any individual case depends on the shape and structure (surface-mass ratio) of the particles and on the velocity of the wind. The

[a] Amer. jour. sci. (4) **19**: 167 (1905).

[b] Bull. Geol. soc. Amer. **19**: 90 (1908); Jour. Geol. **17**: 659–663 (1909).

[c] For a case (in the Holland dune lands) see Du Bois—Tijd. Aardr. Gen. **26**: 869–910 (1909).

[d] Verh. Ges. Erdk. Berlin **19**: 52–65 (1892); translated in Nat. geog. mag. **4**: 163–208 (1892). On the eolian formation of cirques, see also Barron and Hume—Topography of the Eastern desert of Egypt, p. 289 (1902).

[e] Bull. Mus. comp. zool. **38**: 187–191 (1901).

[f] Bull. Geol. soc. Amer. **19**: 61–62 (1908).

[g] Jour. geol. **17**: 150 (1909).

[h] On the eolian interchange of dust between different regions, see Gessert—Naturw. Wochens. **22**: 705–707 (1907).

[i] This term is employed by geologists to indicate the size of the particle of solid matter which can just be carried by a stream—the largest particle which the stream is "competent" to handle. The extension of the term to eolian transport is obvious.

latter factor is ordinarily the more important, since most soil particles (except the micas) are approximately spherical. The forces which tend to place a particle in suspension and keep it there have been explained as due to the impact of the air against the particle and the "friction" of the air in passing it. The commonly used formula of Stokes[a] (which makes no distinction between these quantities) expresses the relation between velocity and radius of a sphere moving through a fluid as $V=\frac{F}{6\pi\eta r}$; in which V is the velocity, η the viscosity constant of the fluid, r the radius of the sphere, and F the force which causes the motion. In the case of solid particles suspended by the wind this force is that of gravity, and if its value in terms of the radius be introduced in the above formula, the latter becomes $V=\frac{2g}{9\eta}r^2$ or $V=Kr^2$, where K is a constant for spherical particles of uniform specific gravity. This means that the wind velocity necessary to support a particle will vary as the square of the radius; or inversely, the radius of the particle which the wind can support (the radius of competence) will vary as the square root of the velocity. An increase in wind velocity will, according to this formula, produce a less than corresponding increase in competence. The same formula ($V=Kr^2$) may be easily deduced from a consideration of the loss of momentum by impact of moving air particles against a sphere. Unfortunately this formula does not seem to be in very good agreement with the rather meager experimental data. The formula of Stokes has been tested by Zeleny and McKeehan[b] and by Buller[c] for the case of the fall of plant spores in still air. Both observers find a discrepancy of about 50 per cent between theory and observation, but in opposite directions. Zeleny and McKeehan find that the observed values are less than the calculated, while Buller finds the reverse. Zeleny and McKeehan, however, in a preliminary announcement of later work[d] say that Stokes's formula has been found to hold for the fall of small spheres of wax, paraffin, and mercury. Thoulet[e] has also tested the relations concerned by measuring the size of approximately spherical quartz grains which were kept just suspended by an upward air current of known velocity in a narrow, vertical tube. His data are given in Table II.

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[a] Trans. Camb. Phil. Soc. **9**, II: [51]–[52] (1850).

[b] Science (n. s.) **29**: 469 (1909); Nature **81**: 472 (1909).

[c] Nature **80**: 186–187 (1909).

[d] Nature **82**: 158 (1909).

[e] His earlier experiments were made in 1884 and are reported in Ann. mines (8) **5**: 526–530 (1884). His later, more exact experiments are reported in the Compt. rend. **146**: 1185 (1908). In the table the data of both articles are combined. The values from the earlier experiments are marked with an asterisk.

TABLE II.—*Measurements by Thoulet on the size of quartz grains kept suspended by a uniform upward current of air.*

Wind velocity. Meters per second.	Diameter of quartz particles.	Wind velocity. Meters per second.	Diameter of quartz particles.	Wind velocity. Meters per second.	Diameter of quartz particles.	Wind velocity. Meters per second.	Diameter of quartz particles.
	Mm.		*Mm.*		*Mm.*		*Mm.*
0.50	0.04	3.00	0.25	6.30	0.53	10.00	0.81
1.00	.08	3.60	.31	6.95	.56	*10.80	.38
*1.51	.14	4.30	.35	7.00	.57	11.00	.89
2.00	.16	4.75	.39	7.70	.62	12.00	.97
*2.25	.27	5.00	.41	8.00	.65	13.00	1.05
*2.67	.29	5.60	.47	8.10	.65		
2.95	.34	6.00	.49	9.00	.73		

Thoulet himself makes no deductions from these experiments, but on plotting his results it is evident that the relation is linear and corresponds to the formula $V = Kr$, where K is a constant for the conditions of the experiment. The discrepancy between this result and the formula deduced from the Stokes equation is not easy to explain. It is possible that the relations existing in a narrow tube are not similar to those for free motion in the open air. The recent experiments of Orsi[a] do not cover wide enough ranges of sizes and velocities to be useful for a checking of the formulæ. They do, however, lead to the interesting conclusion that the velocity of moving air relative to its surroundings has a marked effect on the rate of fall (relative to the air) of particles through it.

Closer to the actual conditions in nature are the observations of Udden[b] on the paths of particles of various size allowed to fall freely when the wind was blowing with a velocity of approximately 8 miles an hour (3.58 meters a second). It was found that particles averaging 0.75 mm. in diameter fell in a path differing but 10° from the vertical. Those averaging 0.37 mm. fell at an angle of about 45°, while those averaging 0.18 mm. followed a path differing but little from the horizontal. Material 0.08 mm. and less in diameter was blown clear away.

In all the above discussion the velocities mentioned are, of course, the velocities of the wind with reference to the particles (or vice versa), and only the components of these velocities parallel and opposite to the force of gravity are of interest. The velocities of the wind itself or of the particle as referred to any point in space or to a point on the surface of the earth are of no direct interest in calculating the supporting power. However, the upward velocities of the momentary cross currents (see p. 33) to which support is due may, in a general way, be assumed proportional to the velocity of transla-

[a] Arch. Hygiene 68: 22–53 (1908). [b] Jour. geol. 2: 324 (1894).

tion of the wind as referred to the earth's surface, though it is not impossible that they may increase in greater ratio.

As a practical deduction from his experiments and from many measurements of blown dust from many different sources Udden[a] concludes that the "average largest size of quartz particles that can be sustained in the air by ordinary strong winds is about 0.1 mm. in diameter." This conclusion seems to be in good agreement with all known data.[b] It applies only to particles which are sustained in the air. The size of the grains which can be rolled and drifted along the surface depends not alone on the wind velocity and the nature of the material, but obviously on the topography as well. Mechanical analyses of dune sands from different localities show the presence of material varying between fairly wide limits,[c] but this, of course, means little, as the history of the sand is usually not fully known, nor is it possible to say in how far it owes its position exclusively to eolian action. Experiments on the wind velocity required to drift sand of definite size under definite conditions have been made by Sokolov[d] and Olsson-Seffer,[e] but it is difficult to draw from them any conclusions of general applicability.

Mushketov[f] and Walther[g] think that the largest particles which can be moved (not sustained) by ordinary strong winds are about 2 mm. in diameter. Winds of extraordinary strength may, of course, move larger fragments. For instance, Rohlfs[h] and Przhevalskii[i] have seen stones as large as the fist blown along by the wind in the deserts of Sahara and Gobi, respectively. R. W. Pumpelly[j] saw stones 2 inches across blown along by a storm in Turkestan.

It is said[k] that a wind-borne pebble 2 cm. in diameter was collected from the snow on Ben Nevis after a severe storm.

In all such cases it is necessary to discriminate between material moved by the wind and material moved by gravity with the assistance of the wind. On sloping ground the wind is able to dislodge and start off rock fragments far too large to be affected by it on the level. In any event the movement of occasional large stones is of interest only as a curiosity. Of the particles moved to any distance, by far the larger number must lie well inside of Udden's limit of 0.1 mm.

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[a] Jour. geol. **2**: 318–331 (1894). See also his "Mechanical composition of wind deposits," where many mechanical analyses are given.

[b] Cf. Table III, p. 45, below.

[c] See p. 68, below.

[d] Venukoff—Compt. rend. **100**: 473 (1885); Sokolov—Die Dünen, p. 12 (1894).

[e] Jour. geol. **16**: 553–558 (1908).

[f] Nature **34**: 237 (1886).

[g] Wüstenbildung, p. 97.

[h] Quer durch Afrika, vol. 1, p. 216 (1874); Ausland **45**: 1112 (1872).

[i] Diener—Peterm. Mitth. **35**: 3 (1889).

[j] Carnegie Institution of Washington Pub. **73**: vol. 2, p. 303 (1908).

[k] Murray and Renard—Nature **29**: 590 (1884). On pebbles moved by storms in the Alps see Theobald—Jahrb. Schweizer Alpenklubs **4**: 534–535 (1867–68).

For purposes of reference some measurements of the size of undoubted wind-borne particles are given in Table III.

TABLE III.—*Maximum size of particles in various samples of air-borne dusts.*

No.	Description.	Maximum diameter.
		Mm.
1	Dust from storm at Irvington, Ind., January 11, 1895	0.05
2	Dust from storm in New South Wales	1.00
3	Dust from Australian storm, fallen in New Zealand	.03
4	Dust fallen in Chile, November, 1883	.01
5	Sirocco dust fallen at Rome (no date)	.07
6	Sirocco dust from fall of March 24, 1869	.01
7	Sirocco dust fallen at Lesina, Austria, 1879	.07
8	Sirocco dust fallen at Klagenfurt, Austria, November 14, 1885	.0324
9	Sirocco dust fallen in Hungary, February, 1888	.07
10	Sirocco (?) dust fallen in Sweden, May 3, 1892	.01
11	Sirocco dust fallen at Florence, Italy, March, 1900	.01
12	Sirocco dust fallen at Engadine, Switzerland, March, 1901	.09
13	Sirocco dust fallen at Zurich, Switzerland, March, 1901	.01
14	Sirocco dust fallen at Vienna, Austria, March, 1901	.02
15	Sirocco dust fallen at Kufstein, Austria, March, 1901	.06
16	Sirocco dust fallen at Zell-am-See, Austria, March, 1901	.06
17	Sirocco dust fallen at Eisenerz, Austria, March, 1901	.05
18	Sirocco dust fallen at Neiderdorf, Austria, March, 1901	.05
19	Sirocco dust fallen at Arnoldstein, Austria, March, 1901	.05
20	Sirocco dust fallen at Kirchbach, Austria, March, 1901	.10
21	Sirocco dust fallen at Tarvis, Austria, March, 1901	.07
22	Sirocco dust fallen at Görz, Austria, March, 1901	.075
23	Sirocco dust fallen at Lesina, Austria, March, 1901	.07
24	Sirocco dust fallen at Fiume, Hungary, March, 1901	.051
25	Sirocco dust fallen at Budapest, Hungary, March, 1901	.11
26	Sirocco dust fallen at Stuttgart, Germany, March, 1901	.04
27	Sirocco dust fallen at Cismar, Germany, March, 1901	.04
28	Sirocco dust fallen at Bremen, Germany, March, 1901	.10
29	Sirocco dust fallen at Hamburg, Germany, March, 1901	.10
30	Sirocco dust fallen at Rorschach, Switzerland, February, 1903	.20
31	Sirocco dust fallen at Travers, Switzerland, February, 1903	.20
32	Sirocco dust fallen at Zurich, Switzerland, February, 1903	.20
33	Sirocco dust fallen at Uccle, Belgium, February, 1903	.05
34	Sirocco dust fallen at Tiel, Holland, February, 1903	.07
35	Sirocco dust fallen at Lausanne, Switzerland, February, 1903	.02
36	Sirocco dust fallen at Les Amerois, Belgium, February, 1903	.12
37	Sirocco dust fallen on steamship Sparta, 26° N., 22° W., February, 1903	.162
38	Sirocco dust fallen on steamship Holsatia, 28° N., 20° W., February, 1903	.072
39	Sirocco dust fallen on steamship Carl, 40° N., 24° W., February, 1903	.288
40	Sirocco dust fallen at Ponta Delgada, Azores, February, 1903	.416
41	Sirocco dust fallen on steamship Hogarth, 13° N., 26° W., February, 1903	.62
42	Atmospheric dust	.01
43	.....do	.10
44	Atmospheric dust from Paris	.10
45	Dust from snow, from Paris	.01

AUTHORITIES FOR ABOVE TABLE.

1. Bruner—Mon. weather rev. **23**: 18 (1895). A sample of dust which fell at Madison, Wis., during the same storm was kindly furnished to me by Prof. J. A. Jeffery. It has been examined by Dr. C. C. Fletcher, of this laboratory, who found the maximum size of the component particles to be 0.06 mm. Complete mechanical analyses of dust deposited by this storm at York, Nebr., were made by Prof. Milton Whitney, of this Bureau, and are reported by Barbour—Rept. Nebr. state board of agr. **1896**: 168. Material was found up to 0.5 mm. in diameter, but it may have been partly of local origin.
2. Liversidge—Jour. Proc. Roy. soc. N. S. Wales **36**: 244 (1902).
3. P. Marshall—Nature **68**: 223 (1903).
4. N. A. E. Nordenskiöld—Geol. fören. förh. **8**: 451 (1886).
5. Clerici—Boll. Soc. geol. ital. **21**: xl (1902).
6. Ehrenberg—Monat. K. Preuss. Akad. Wiss. Berlin **1869**: 308.
7. Hellmann and Meinardus—Der grosse Staubfall, p. 65 (1901).
8. M. Schuster—Sitzungsb. Kaiserl. Akad. Wiss. Vienna **93**: 89 (1886).
9. Camerlander—Jahrb. geol. Reichsanst. **38**: 288 (1888).
10. N. A. E. Nordenskiöld—Met. Zs. **11**: 204 (1894).
11. Achiardi—Atti R. Accad. econ.-agr. Georg. Florence (4) **24**: 145 (1901).
12 to 29. Hellmann and Meinardus—Loc. cit., pp. 60–74.
30 to 34. Früh—Met. Zs. **20**: 174 (1903).
35. Forel—Bull. Soc. vaud. sci. nat. (4) **39**: xxvii (1903).
36 to 40. Herrmann—Annalen Hydrog. **31**: 475–478 (1903).
41. From a mechanical analysis (as yet unpublished) by Prof. J. A. Udden of a sample furnished by the U. S. National Museum. I am indebted to Professor Udden for kindly furnishing me a copy of his results.
42. Ditte—Ciel et terre **25**: 498 (1904).
43. Tissandier—Compt. rend. **81**: 577 (1875).
44. Tissandier—Ibid. **78**: 823 (1874).
45. Tissandier—Ibid. **80**: 59 (1875).

THE TRANSPORT CAPACITY OF THE WIND.

The total amount of material which can be carried by the wind is a matter quite distinct from the question of the size of the particle which it can sustain. It is evident that water is able to carry particles much larger than can be supported by moving air, but in its relation to transport capacity this handicap is more than counterbalanced by the tremendously greater volume of the atmosphere and by the frequently greater velocities possessed by atmospheric currents. The carrying capacity of the wind has been experimentally investigated by Udden,[a] who determined the amount of quartz flour of varying fineness which was kept suspended by air agitated with a velocity of about 5 miles per hour. His results are given in Table IV. No great accuracy is claimed, as the natural conditions are far too complicated to be susceptible to satisfactory reproduction in the laboratory.

TABLE IV.—*Udden's experiments on the quantity of quartz flour kept permanently suspended by air agitated with a velocity of about 5 miles per hour.*

Average diameter of particles.	Quantity sustained per cubic foot.
Millimeter.	*Grain.*
0.08	0.020
.04	.067
.007	.118
.001 (and below).	.053

Udden estimates, from this and other lines of investigation, that under average conditions the atmosphere can hold per cubic foot about 0.0015 gram of solid matter of the average coarseness of river silt. Assuming this value and more or less well-known values for velocities and areas of current, he calculates that the transport capacity of the winds blowing over the basin of the Mississippi is one thousand times as large as the transport capacity of the river. This estimate is based on very conservative data and seems quite worthy of acceptance. If anything it is probably too low.

Of course because the transport capacity of the winds is one thousand times that of the river it does not follow that the actual amounts of material transported are in anything like the same ratio. The atmosphere is usually loaded only to a very small fraction of its capacity, and the river, having so much larger a proportion of its capacity actually utilized, possibly does remove more material from the Mississippi basin than does the atmosphere. The sediment annually discharged by the Mississippi is estimated by Dole and Stabler[b] as 340,500,000 tons, and even if the atmosphere carries only a small frac-

[a] Jour. geol. **2**: 326 (1894).

[b] U. S. Geol. Surv. Water supp. pap. **234**: 84 (1909).

tion of what it is able to carry and only a fraction of what is carried by the river, the amount removed may be still very large.[a] What is the actual amount of atmospheric transportation out of the Mississippi basin, or from place to place within it, it is impossible even to estimate without extensive measurements of deposited dust and of dust in the air over long periods of time. The difficulty of making such measurements is very great and the value of the results obtained would probably be entirely incommensurate with the labor expended. Some idea of the amount of atmospheric transport may be obtained from the various estimates of deposited dust, of deflation, etc., given in the following chapters. Some more or less direct measurements of the material carried by dust-storms are given on pages 80–82. It will be evident that the amount of material moved by the atmosphere is probably very large, and that the maximum amount which could be moved is certainly much larger still.

It may be noted in passing that if these estimates of atmospheric transport can be established they will, to a considerable extent, vitiate the calculations of the rate of geologic denudation which are based on the amount of material carried off by seaward flowing waters.[b]

THE DISTANCE TO WHICH MATERIAL MAY BE CARRIED.

There is a small fraction of the air-borne dust which is fine enough to remain more or less permanently in suspension and the distance to which such material can be carried is limited only by the limits of the atmosphere. But by far the larger part of the material carried by the wind remains in the lower layers of the atmosphere and moves in a series of comparatively short leaps in a manner quite analogous to the process of saltation described by McGee for the detritus of loaded streams and noted on page 33 above. The lengths of the leaps made by the individual particles depend on their size and shape, on the wind velocity, and to a certain extent on the topography of the country. Very heavy particles, the coarsest of the drifting sand, are dislodged by some unusually heavy gust and carried forward a distance dependent largely upon the initial impulse and the force of gravity, the resistance (or assistance) of the air being relatively unimportant. Such a particle will describe a trajectory, which is sensibly a parabola. With decrease in the size of particle, the assisting action of the wind becomes of greater and greater importance and the path departs more and more from the parabolic form, tending in the limiting case (and when variations in direction of the air currents are neglected) to approach the straight

[a] On the presence and importance of air-borne dust on the ocean bottoms, see Thoulet—Compt. rend. **146**: 1184–1186, 1346–1348 (1908); **148**: 445–447 (1909) and **150**: 947–949 (1910). Cf. Murray—Proc. Roy. geog. soc. (n. s.) **12**: 465 (1890).

[b] Free—Science (n. s.) **29**: 423–424 (1909).

line parallel to the direction of the wind, which represents the path described by the truly suspended particle. In all actual cases the path described is affected by so many accidental variations that it loses all resemblance to any regular curve, but the motion is always saltatory in its general character and all eolian transportation (excluding that of truly suspended material) is by a series of leaps. This manner of progression can be very easily and very beautifully observed in the motion of drifting sand under a moderate wind.[a]

With such sand the leaps are very short—a few inches or a few feet—but the finer material intermediate between that in saltation and that in true suspension may make leaps of much greater length, perhaps even of miles. The particular sizes (or surface-mass ratios) which such material includes will vary with the velocity of the wind. A heavy storm may carry in what is practically permanent suspension matter which, by ordinary winds, would be moved only in saltation. There is really no intrinsic difference between saltation and suspension. Particles carried in suspension are simply saltatory particles whose leaps are disproportionately (in the limiting case infinitely) long.[b] This intermittent character of the movement of soil particles by the wind applies, of course, only to individual particles and not to the mass, and does not mean that the air intermittently loses its load. When one particle is dropped another is picked up, and the total load may remain practically constant, though the individual particles are changing. Neither does it mean that an individual particle can not travel far if sufficient time be allowed. Unless in some way permanently attached to the surface some of the particles dropped at any spot will be again picked up and started on another leap. The total distance of transport effected by even one storm may be very considerable for some few of the particles. Others will be left from place to place along the way and new ones picked up in their stead. It is this constant interchange which takes place between the atmospheric load and the soil which gives to the process of wind translocation its importance in mixing soils and maintaining their heterogeneity.

The arid region dust storms, described on page 77 and following, frequently carry material so fine that much of it remains in suspension throughout the whole course of the storm, and the distances covered by such material are consequently very great, though well-

[a] See the recent experiments of Olsson-Seffer on drifting coastal sands, Jour. Geol. **16**: 557–558 (1908).

[b] Saltatory transport is here discussed as though the wind were constant in direction and velocity. Of course, in nature this practically never occurs; and owing to eddies and velocity changes in the wind a particle of medium size may be successively in "suspension" and in "saltation" a score of times in the course of a single "leap." The path actually followed by a wind-borne particle is indescribably complex.

established instances are rare on account of the difficulty of determining the source of the material. Examination of the dust itself usually fails to indicate the place of origin, and one must rely on indirect evidence, such as the existence of a probable source in the direction from which the wind was coming, meteorological data by which the path of the storm can be traced, etc. A few instances of long-distance transport by dust storms are given on pages 82–83.

It occasionally happens that dust is raised into the upper air by violent storms, volcanic eruptions, etc., and the possible velocities and distances of transfer are then much greater, not alone on account of the greater vertical fall available, but because of the greater velocity of the air currents at higher altitudes. Observations on cloud movements [a] have shown the presence of rapid currents at heights of from 2 to 10 miles, and the recent observations of Trowbridge [b] on meteor trains indicate that velocities of over 100 miles per hour are not infrequent at greater heights (40 to 65 miles). The existence of cloud glows and similar optical effects due to dust shows that some dust is present at high altitudes, though perhaps not at the highest mentioned, and what dust is there will travel far and fast. The European dust storm of February, 1903, seems to have traveled mainly in the higher strata and with a velocity of about 50 miles an hour.[c] A part of the dust of the storm of March, 1901, also got into the higher strata (above the zone of rain formation) and was not precipitated with the rain of March 12. Three days later it had sunk low enough to be caught by the rain of the 15th and carried down therewith.[d] It is probable, however, that the total transport affected by these higher currents is very slight. Most eolian transportation is by saltation in the air close to the surface.

THE DEPOSITION OF ATMOSPHERIC LOAD.

Material carried either in suspension or in saltation is deposited primarily by decrease of wind velocity. Owing, however, to the variable character of the wind, and indeed to the very nature of the process of saltation, material is always being deposited and other material being picked up. The problems of the accumulation of blown material are therefore not so much problems of deposition as problems of the retention of the material which is deposited.[e] As,

[a] See, e. g., Polis—Met. Zs. **19**: 441–453 (1902).

[b] Mon. weath. rev. **35**: 390–397 (1907).

[c] Herrmann—Annalen Hydrog. **31**: 481 (1903).

[d] Krebs—Annalen Hydrog. **31**: 174 (1903).

[e] The action of rain in washing dust out of the air and thus causing its deposition is not of great geological importance. In so far as it causes the deposition of truly suspended atmospheric dust it will be later discussed under that head.

however, the removal of material depends upon the violence of the wind as much as does its transport, the problems of retention come back pretty closely to wind velocity after all. What decreases the wind velocity will favor retention as well as deposition. Thus the action of vegetation in causing the deposition (or rather the accumulation) of blown material depends primarily upon the decrease of wind velocity produced by the vegetal obstruction, but this decrease of velocity both causes the wind to deposit its suspended matter and prevents its picking up new.

On account of their retentive action plants are particularly efficient in collecting drifting sand and other material which moves near the surface in a succession of comparatively short leaps. A clump of plants in an area of moderate sand drift will thus collect blown material around it, forming a little mound. As the sand heap grows the plants grow also and continue their accumulating action until a heap several feet high may be produced. These plant-formed mounds, both of sand and of fine dust, occur very commonly in the arid and semiarid regions [a] and have been noticed by many travelers.[b]

It is obvious that similar mounds may be produced by the removal of soil from the intervening spaces instead of by accumulation at the locus of the plant.[c] In fact, in the cases of many of these desert mounds it is impossible to decide whether they have been formed by accumulation or by retention coupled with lowering of the general surface. Probably both agencies are often at work at once. Because of the great mobility of the surface material of deserts the plant-

[a] Their universality in such regions is large due to the tendency of desert plants to grow in clumps or colonies with bare spaces between. These isolated colonies easily catch the blown dust and sand.

[b] See, e. g., Ehrenberg—Abh. K. preuss. Akad. Wiss. Berlin **1827**: 73-88; Wellsted—Travels in Arabia, vol. **1**, p. 87; vol. **2**, p. 38 (1838); Kinahan—Nature **16**: 7 (1877); Gabb—ibid., pp. 183-184; Senft—Gæa **15**: 83-92 (1879); Tarr—Amer. nat. **24**: 458 (1890); Means and Gardner—Field Operations, Bur. of Soils, **1899**: 62; Walther—Wüstenbildung, pp. 122-124, 128, etc. (1900); Russell—U. S. Geol. surv. Bull. **217**: 33 (1903); MacDougal—Bot. gaz. **38**: 52 (1904), Bull. Amer. geog. soc. **39**: 709-710 (1907), North American deserts, p. 37, 39 (1908); Hedin—Scientific results, vol. **1**, p. 332 (1904); vol. **2**, p. 15 (1905); Grund—Sitzungsb. K. Akad. Wiss. Vienna Abt. I, **115**: 550 (1906); Hume—Topography Southeastern Sinai, p. 65 (1906); Hill—Eng. min. jour. **83**: 663 (1907); Hovey—Bull. Amer. mus. nat. hist. **23**: 405 (1907); S. H. Ball—U. S. Geol. surv. Bull. **308**: plate II (1907); Beadnell—An Egyptian oasis, p. 78-80, 210 (1909); Stein—Sand buried ruins of Khotan, pp. 275, 429, 435 et al. (1903), Geog. jour. **34**: 24 (1909); Spalding—Distribution of Desert Plants, p. 11 (1909). Cf. also the observation of Przhevalskiĭ of the raising of the banks of central Asian rivers by dust deposited in the vegetation there growing (From Kulja to Lob Nor, p. 57 [1879]).

[c] For examples see MacDougal and Grund (loci citati in last note), Baraban—À travers la Tunisie, p. 76 (1887); Ivchenko—Ann. géol. min. Russ. **7**, I: 50, 53 (1904); Huntington—Pulse of Asia, p. 180-181 (1907); and Waring—U. S. Geol. surv. Water supp. pap. **220**: 11, plate III, b (1908).

protected spots tend to grow quite rapidly at the expense of the interspaces which lack this advantage, and the producers of this growth are seldom exclusively eolian. The plants act toward the water-borne detritus much as they act toward that moved by the wind.

Forms of protection other than vegetal will also serve to prevent removal, though they have usually no tendency toward localizing accumulation. The writer has frequently seen mounds and ridges capped with desert pavements, and it seems not improbable that these elevations owe their origin to the pavement which protects them. The surrounding depressions, having lacked this protection, or the material from which to produce it, have been more deeply scoured. It is certain that a hard surface layer will serve to localize wind scour and produce gullies and local depressions where the protecting layer is absent or breached.[a] The clay "eolian mesas" and wind-scoured gullies of the desert of Lop-Nor[b] have probably been formed in somewhat this way,[c] though the past distribution of vegetation may have been not without influence.[d] Forms superficially similar to these, but on a smaller scale and composed of hardened dune sand, are not uncommon in the wind-scoured parts of dune areas. The best examples which the writer has examined are in the gypsum dunes of the Alamogordo desert.[e] In this area the taller sand blocks are usually capped by plants, which have probably had much to do with their formation.

In the humid regions the action of vegetation is not so noticeable, because the plants do not grow in clumps and no raised mounds are produced, but the action is none the less present and the blown dust entangled in the vegetation goes to raise the general soil surface over areas in which deposition is in progress. In the general movement of detritus from place to place land covered with vegetation is better able to retain material which falls on it, and it therefore happens that vegetation-covered areas, large or small, tend to gain at the expense of those not so covered. This growth of soil, because of the retention

[a] For examples see Rolland—Géologie Sahara algérien, p. 215–217 (1890); Russell—U. S. Geol. surv. Bull. **199**: 144 (1902); and authorities cited in the next note below. A similar case of eolian undercutting in soft tuffs capped by a harder layer is cited by Hovey—Bull. Amer. mus. nat. hist. **23**: 429–430, and plate xxlx (1907).

[b] Hedin—Scientific results, vol. **2**, p. 67, 223–253, 488–489, 494–500 (1905); Huntington—Pulse of Asia, p. 253–254, 262 (1907); Stein—Ancient Khotan, pp. 107–108, 112, 242, 315, 327 (1907), Geog. jour. **34**: 26 (1909); R. W. Pumpelly—Carnegie inst. of Wash. Pub. **73**, vol. **2**, pp. 283–284 (1908). Similar forms in the Oasis of Kharga (Egypt) are mentioned by Beadnell—An Egyptian oasis, p. 111 (1909).

[c] Hedin—Loc. cit., p. 238.

[d] Hedin—Loc. cit., pp. 248, 365.

[e] Noted by MacDougal—Botanical features of North American deserts, p. 13, and plate 2 (1908).

of blown dust by the vegetal covering, has been observed by Shimek [a] and Shaler,[b] and especially by Huntington.[c] According to the last writer the areas over which eolian loess is now being deposited in central Asia are determined by the presence or absence of vegetation, which in turn is determined by the general climatic conditions.[d] The periods of greater rainfall which are postulated by his hypothesis of alternating climatic change, are also periods of greater vegetation, and therefore periods of loess accumulation; and with change of climate, either toward or away from greater aridity, the vegetation will increase or disappear, will retreat or advance, and the areas of eolian accumulation or removal will vary accordingly. Another interesting illustration is the observation of Beadnell[e] that the irrigated and cultivated spots in the Oasis of Kharga in the Lybian Desert have been raised many feet within historic times simply by the accretions of wind-blown dust and sand which they are constantly receiving and which are retained by their vegetal covering.

Of course, decrease of wind velocity and consequent deposition may occur in ways with which vegetation or other surface obstacles have nothing to do; ways which are much more general and affect much larger areas. The more or less constant winds, which are caused by climatic and general meteorological conditions or by the larger features of the topography, often tend to lose their velocity over about the same area, and if these winds be dust-laden this area will become one of eolian deposition. Of course there must be somewhere complementary areas of eolian removal from which the winds have obtained their load. The accumulation of eolian material over wide areas, and even in some cases over small ones, is dependent in the most complex way upon climatic factors, not alone as they influence the path and velocity of the winds, but even more as they control the presence or absence of vegetation and its nature and permanence. These matters will find ample illustration in the discussion of the loess and its probable origin, which will be found on pages 124 to 141.

Accumulation in special locations may also be caused by the direct action of a moist surface in retaining particles which accidentally drop thereon. Thus the initial impulse to dune formation is occasionally furnished by a moist spot, which causes the accumulation of a

[a] Proc. Iowa acad. sci. **4**: 68–72 (1897); **10**: 45–48 (1903); **15**: 57–64 (1908).

[b] Bull. Geol. soc. Amer. **10**: 245–252 (1899).

[c] Bull. Geol. soc. Amer. **18**: 359–360 (1907), and Pulse of Asia, pp. 135, 148 (1907), See also Richthofen—Führer für Forschungsreisende, pp. 477–483 (1886), and Hedin—Scientific results, vol. **1**, p. 291–293 (1904).

[d] See also R. W. Pumpelly—Carnegie inst. of Wash. Pub. **73**, vol. **2**, pp. 246 et al. (1908).

[e] An Egyptian oasis, pp. 78–80, 210 (1909).

heap of sand,[a] and it has been suggested by Fischer [b] that on the coast of Morocco moisture (especially dew) assists the growth of soil by entrapping and retaining fallen eolian dust. It is necessary of course that the surface be possessed of a sufficient supply of moisture to resist the drying action of the wind, and it is apparent from the discussion on page 30 that most land areas are not thus equipped. Any surface will meet the conditions just after a rain, but very few are wet enough to do so at all times. The extreme case is that in which dust falls on the surface of the water itself. Such material goes to join the load of the stream or is deposited on the bottom of the lake or sea.[c]

Another interesting special case is the tendency of the salts of certain alkali soils to keep them moist and thus cause the accumulation of dust. It is possible that some few deposits of loess have been formed in this way.[d]

DRIFTING SAND AND SAND DUNES.

THE NATURE OF SAND DRIFT.

The ordinary drifting sand moves in saltation by comparatively short leaps, never rising far above the surface.[e] That of the desert can not be felt by a person mounted on a camel.[f] By reason of this tendency to hug the surface, isolated rocks exposed to drift-sand corrasion are worn away much more rapidly below than above, assuming various mushroomlike forms,[g] and trees, telegraph poles, etc., are girdled near the ground.[h]

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[a] Garnier—Compt. rend. Soc. géog. Paris **1885**: 498–499; Courbis—ibid. **1890**: 114–119, 256–261; Cornish—Geog. jour. **15**: 28–30 (1900); MacDougal—Botanical features of North American deserts, p. 39 (1908); Ivchenko—Ann. géol. min. Russie **10**, I: 20–21, 25–26 (1908).

[b] Peterm. Mitth. Ergänzungs hft. **133**: 122–123 (1900), Mitth. geog. Ges. Hamburg **18**: 1155 (1902).

[c] See Hedin—Scientific results, vol. **2**, p. 132–133 (1905).

[d] Rolland—Compt. rend. **114**: 1298–1301 (1892); Walther—Wüstenbildung, p. 112 (1900).

[e] See Brémontier—Ann. ponts chauss. **5**: 148 (1833); Blake—Pacific Railway repts. vol. **5**, p. 242 (1856); Travers—Trans. New Zealand inst. **2**: 248 (1869); Wesseley—Flugsand, p. 51 (1873); Beringer—Documents Mission Flatters, p. 92 (1884); Sokolov—Die Dünen, pp. 14–15 (1894); Hedin—Through Asia, vol. **1**, p. 516 (1899); Hornaday—Campfires on desert and lava, p. 187 (1908); etc., and especially the experiments of Olsson-Seffer—Jour. geol. **16**: 553–558 (1908). On the similar drift of snow in the arctic see Andrée—Arch. sci. phys. nat. Geneva (3) **15**: 522–533 (1886); Kusnezov—Meteor. Svornik **1900**: 477–481; Ferrar—National Antarctic Exped. 1901–4, Nat. Hist. **1**: 84 (1907); and Tschirwinsky—Zs. Gletscherk. **2**: 104–112 (1907).

[f] Foureau—Documents scientifiques Mission saharienne, vol. **1**, p. 215 (1904).

[g] See e. g., Hedin—Through Asia, vol. **1**, p. 445 (1899); Jentzsch—Gerhardt's Handbuch des Dünenbaues, p. 57 (1900); Cornish—Geog. jour. **15**: 21 (1900); R. T. Hill—Eng. min. jour. **85**: 686, and photo. on page 685 (1908); Tolman—Jour. geol. **17**: 150 (1909).

[h] Udden—Pop. sci. mon. **49**: 663 (1896); MacDougal—Botanical features of North American deserts, p. 38 (1908). Cf. also p. 27 above. Dr. W J McGee tells me that the Casa Grande Ruins in Arizona have been reduced to their present dilapidated state largely by the sapping of the walls by drift sand.

The phenomena of sand drift are most clearly and strikingly exhibited on nearly level plains of some extent, covered with loose sand, and, in the main, free from vegetational or other obstructions. Such plains, of glacial, fluvial, marine, or eolian origin, are not uncommon in nature and form the sand wastes of the various continents,[a] as well as the sandy portions of the true deserts.[b] Borders of drifting sand are also found on many coasts where the sand supplied by the sea is carried inland by on-shore winds.[c] These natu-

[a] On these sand wastes see: Gutbier—Sitzungsb. Isis Dresden **1864**: 42–54; Wesseley—Der europäischen Flugsand und seine Kultur, 1873; Mangin—Le désert et le monde sauvage, 1866; and works cited in the bibliography under Deminskĭĭ, Friedberg, Garkem, Gerasimov, Gottlieb, Graebner, Griselini, Gutbier, Hult, Ispolatov, Lakin, Lehmann, Lorié, McMaster, Morlot, O. T., W. Peters, Pravitelstven. Vĕstnik, Praxa, Raznochintsev, S. S., Sabban, Solon, Stache, Suomalainen, Themák, Timoshchenkov, Uspenskĭĭ, V. M., Vorreith, Wahnschaffe, and H. Wolf.

[b] The literature of deserts is too extensive to permit of summary. A few of the more important works are referred to on the following pages and cited in the bibliography. On desert geology in general see Walther—Das Gesetz der Wüstenbildung, 1900; Wohlfarth—Zür Morphologie der Wüsten, 1902; Wiszwianski—Die Faktoren der Wüstenbildung, 1906; Penck—Geog. Zs. **15**: 545–558 (1909).

[c] On coastal sands and dunes see Forchhammer—Neues Jahrb. Min. **1841**: 1–38, Andresen—Om Klitformationen, 1861; Keller—Zs. Bauwesen **31**: 189–210, 301–318, 411–422 (1881); **32**: 19–35, 162–179 (1882); Wesseley—Flugsand, p. 25–31 (1873); Jentzsch, in Gerhardt's Handbuch des deutschen Dunenbaues, p. 41–124 (1900); Reinke—Wiss. Meeres-unters. Kiel (n. f.) **8**, Ergänzungsh. (1903); Ibid. n. f. **10**, Ergänzungsh. (1909). For other works and descriptions of special localities (not North American) see the works cited in the bibliography under About, Ailio, Albert, Alker, Andresen-Rabenholz, Arctowski, B., Auerbach, Bagneris, F. Bailey, Baschin (Dünenstudien), Baude, Baudissin, Bayberger, Berenberg, Berendt, Berghaus, Bert, Bezzenberger, Blesson, Blijdenstein and Brants, Boase, Borggreve, von dem Borne, Bortier, Braine, Branner (Amer. jour. sci. (4) **16**: 307 [1903]), Brémontier, J. C. Brown, Brüel, Buffault, Camerer, Chambrelent, Cockayne, Coincy; F. W. Conrad, Czerny (p. 27), Dahms, Dawkins, Deecke, De la Beche, Delamarre, Delfortrie, C. W. Dorsey (Bull. Phil. Bur. agr. **3**: 22 [1903]), Doss, Duffart, Durègne, Edmonds, Élie de Beaumont (Leçons, vol. **1**, pp. 195–220), Engell, Engler, Fabre, Faye, Feilberg, Feldt, Fisher, Foote, Foss, Frömbling, Archibald Geikie (Textbook, pp. 441–443), Gillet-Laumont, Girardin, Goursand, Grandjean, Hagen, T. S. Hall, Hallier, Harder, Harshberger, Hartig, Hauser, Hautreux, Hesselman, Heywood, Hodgkin, Hooker and Ball (pp. 81, 324–325), Hübbe, Hull, Jachmann, Jentzsch, Keilhack, Kennard and Warren, Kinahan, Wm. King and Foote, Klinge, Klinsmann, Knuth, G. C. A. Krause, Labat, de Lambrardie, Laval, Laveleye, Lehmann, Leiviskä, Le Mang, Linck, Lindner, Lorentzen, Lorenzen, Lorié, Maack, McNaughton, Magalhães-Mesquita, Marshall, Massart, Maw, Meier, Meinicke, Meyn, Mickwitz, Monckton, Mortensen, Müller, E. Naumann, Nilsson, Parran, Pechuel-Loesche, E. Philippi, Pigeon, Poboguin, Poisson, Poore, Pravitelstven. Vĕstnik, Prestwich, Razeburg, Reclus, C. Reid, Reinke, Riefkohl, Rosberg, Saint-Jours, Samanos, Schumann, Sokolov, Sprenger, Stapff, Staring, Steenstrup, Suomalainen, Tassin, Thesleff, Thomson, Toepfer, Topley, Ussher, Vasselot de Régné, Walther (Einleitung, p. 839–844), Webber, Weigelt, Wellsted (vol. **2**, p. 110), Wery, Wessel, Weule, Willkomm, Wilmer, Alec Wilson, T. C. Winkler, Wutzke, Zeise, Zernecke, and Zobrist; also the authorities on dune-control cited on pages 74–75 below.

Published notices and descriptions of North American dune localities (coastal and otherwise) are given in the following list:

Cape Cod: T. Dwight—Travels in New England and New York, vol. **3**, p. 91–92 (1822); Rept. Mass. Commissioners of Cape Cod and East Harbors, 1854; Rept. Chief

ral sand areas of whatever origin are, of course, seldom perfectly level, or entirely free from obstructions, but it is convenient to analyze

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of Engineers U. S. Army, **1876**: 181–190, **1879**: 273–275, **1886**: 574–577, **1903**: 87, 783–784; Westgate—U. S. Dept. Agr. Bur. plant ind. Bull. **65**, 1904; Allorge—Ann. géog. **15**: 443–448 (1906).

New Jersey Coast: Salisbury—The Physical Geography of New Jersey, Final rept. N. J. Geol. surv. **4**: 161–167 (1898); Gifford—Rept. N. J. Geol. surv. **1899**, Forests: 233–318; Harshberger—Proc. Acad. nat. sci. Phila. **1900**: 623–671.

Cape Henlopen, Del.: Rothrock—Proc. Acad. nat. sci. Phila. **1889**: 134–135.

Cape Henry, Va.: Kearney—Contrib. U. S. nat. herb. **5**: 332–337 et al. (1901); Darton—U. S. Geol. surv. Geol. atlas U. S. folio **80** (Norfolk) (1902).

The Hatteras Banks, N. C.: Kerr—Bull. Phil. soc. Wash. **6**: 28–30 (1884); Kearney—Contrib. U. S. nat. herb. **5**: 261–319 (1900); Cobb—Nat. geog. mag. **17**: 310–317 (1906), Jour. Elisha Mitchell sci. soc. **22**: 17–19 (1906); J. H. Pratt (and Bond)—ibid. **24**: 125–138 (1908).

Pacific coast: Lamb—Forester **3**: 94 (1897); Davy—U. S. Dept. Agr. Bur. plant ind. Bull. **12**: 65–57 (1902); H. P. Baker—Proc. Iowa acad. sci. **13**: 214 (1906); Humphrey—Plant world **12**: 79–82, 152–157 (1909).

Adair Bay (Gulf of California): Sykes, in Hornaday—Camp fires on desert and lava, p. 231 (1908); MacDougal—Bull. Amer. geog. soc. **40**: 719 (1908).

Southern end of Lake Michigan: E. J. Hill—Garden and forest **9**: 353–354, 372–373, 382–383, 393–394 (1896); Cowles—Bot. gaz. **27**: 95–117, 167–202, 281–308, 361–391 (1899); Coulter—Proc. Ind. acad. sci. **1906**: 122–128; de Vries—Album der natuur **1906–7**: 129–141, 161–178.

Along the Columbia River: Hitchcock—Nat. geog. mag. **15**: 44 (1904); Willey—Sci. Amer. supp. **65**: 113, 120–121 (1908).

Arkansas River Valley (eastern Colorado and western Kansas): Hay—U. S. Geol. surv. Bull. **57**: 44–45 (1890); Haworth—Univ. Geol. surv. Kans. **2**: 276–279 (1897), U. S. Geol. surv. Water supp. pap. **6**: 24–25 (1897); Darton—U. S. Geol. surv. Prof. pap. **52**: 35 (1906).

Sheyenne Delta, North Dakota: Willard—Story of the Prairies, 5th ed., p. 94–95 (1908).

Northeastern Iowa: McGee—Ann. rept. U. S. Geol. surv. **11**, I: 453 (1891).

Western Iowa: Shimek—Bull. Lab. nat. hist. Univ. Iowa **5**: 374 (1904).

Central Illinois: McDonald—Plant world **3**: 101–103 (1900); Hopkins and Pettit—Ill. agr. expt. stat. Bull. **123**: 246 (1908).

Minnesota: Upham—Final rept. Geol. and nat. hist. surv. Minn. **2**: 418 (1888); Sardeson—Amer. geol. **20**: 392–403 (1897); Elftman—ibid. **21**: 90–109 (1898); C. W. Hall and Sardeson—Bull. Geol. soc. Amer. **10**: 349–360 (1899).

Nebraska (sand-hill region): Hayden—Geol. surv. Wyoming, p. 108 (1872); Rydberg—Contrib. U. S. nat. herb. **3**: 135–137 (1895); Todd—U. S. Geol. surv. Bull. **158**: 64 (1899); Darton—Ann. rept. U. S. Geol. surv. **21**, IV: 549 (1901); U. S. Geol. surv. Prof. pap. **17**: 13, 15, 23 (1903); Lyon—Bailey's cyclopedia of agriculture, vol. **1**, p. 346 (1907); Stevens—U. S. Geol. surv. Water supp. pap. **230**: 220 (1909).

Eastern Oregon and the Snake River Plains (Idaho): Bradley—Ann. rept. U. S. Geol. and geog. surv. terr. **6**: 211–212 (1872); Russell—U. S. Geol. surv. Bull. **199**: 24, 140–141 (1902), Bull. **217**: 30 (1903); Waring—U. S. Geol. surv. Water supp. pap. **220**: 11 (1908).

The Deserts of the Great Basin: Gilbert—U. S. Geol. surv. Monog. **1**: 332 (1890); Russell—U. S. Geol. surv. Monog. **11**: 153–156 (1886); Spurr—U. S. Geol. surv. Bull. **208**: 108 (1903); S. H. Ball—ibid. Bull. **308**: 36, 159, 196 (1907).

Alamogordo Desert, New Mexico: MacBride—Science (n. s.) **21**: 90–97 (1905); MacDougal—Botanical features of North American deserts, pp. 11–16 (1908).

Colorado Desert: Günther—Sitzungsb. K. bay. Akad. Wiss. Munich **1907**: 139–153; MacDougal—Bull. Amer. geog. soc. **39**: 708 (1907), Botanical features of North

the phenomena by considering an ideal level plain of uniform and vegetationless surface on which the sand would drift back and forth from day to day,[a] with a tendency to accumulate in the direction toward which the winds most frequently blew. This drift would be limited in area by borders of mountains, water, or vegetation, but in the direction of prevailing winds the stoppage would be only temporary, for the sand would tend to accumulate just

American deserts, p. 38 (1908); Mendenhall—U. S. Geol. surv. Water supp. pap. **225**: 9–10, 26–27 (1909); Tolman—Jour. geog. —— (1909).

Chihuahua Desert (Mexico): Hesse-Wartegg—Mexico; Land und Leute, p. 25 (1890); Hill—Eng. min. jour. **83**: 663 (1907); Hovey—Bull. Amer. mus. nat. hist. **23**: 404–405 (1907).

Northern Alaska: Schrader—U. S. Geol. surv. Prof. pap. **20**: 95 (1904); Blackwelder—Amer. jour. sci. (4) **27**: 459–466 (1909).

Nova Scotia: L. W. Bailey—Proc. Trans. N. S. Inst. sci. **9**: 180–194 (1896).

Sable Island (off Nova Scotia): Hahn—Meer und Küste **1**: 105–151 (1901); Saunders—Rep. Canada exp. farms **1901**: 62–77, **1902**: 55–58.

Porto Rico: Dorsey et al.—Field oper. Bur. of Soils **1902**: 803, 805.

Dune areas are included in the following sheets of the Topographic Map of the U. S. (U. S. Geol. surv.): Norfolk, Va.; Sandy Hook, N. J.-N. Y.; Ocean City, Md.-Del.; Barnegat, N. J.; Long Beach, N. J.; Green Run, Md.-Va.; Toleston, Ind.; Lakin, Pratt, Larned, Kinsley, Kingsman, Hutchinson, Great Bend, and Dodge, Kans.; Springfield, Colo.; Brown's Creek, St. Paul, and Camp Clarke, Nebr.; and Arroyo Grande and Guadaloupe, Cal.

In the course of the soil surveys conducted by this Bureau dune sands have been found and reported in the following areas (the references are to the Reports of Field Operations of the Bureau of Soils): Merrimack County, N. H. (**1906**: 60–61); Rhode Island (**1904**: 63, 65, 67); Long Island, New York (**1903**: 103, 116); Madison County, N. Y. (**1906**: 140); Niagara County, N. Y. (**1906**: 106, 107, 109); Salem, N. J. (**1901**: 136); Dover, Del. (**1903**: 150); Worcester County, Md. (**1903**: 174, 182–183); Norfolk, Va. (**1903**: 237, 246–247); Raleigh-Newbern, N. C. (**1900**: 200); Chowan County, N. C. (**1906**: 230); Lee County, S. C. (**1907**: 341); Orangeburg, S. C. (**1904**: 200, 201); Sumter County, S. C. (**1907**: 319–320); Charleston, S. C. (**1904**: 213, 221); Escambia County, Fla. (**1906**: 359, 361); Jefferson County, Fla. (**1907**: 374); Meigs County, Ohio (**1906**: 725); Tippecanoe County, Ind. (**1905**: 797); Marshall County, Ind. (**1904**: 699); Newton County, Ind. (**1905**: 761, 767, 768, 769); Winnebago County, Ill. (**1903**: 768, 769); Sangamon County, Ill. (**1903**: 715); Tazewell County, Ill. (**1902**: 470, 471, 473); Biloxi, Miss. (**1904**: 363); Dallas County, Ala. (**1905**: 462–463); Allegan County, Mich. (**1901**: 98–99); Cass County, Mich. (**1906**: 748); Munising, Mich. (**1904**: 588–589); Superior, Wis.-Minn. (**1904**: 760–762); Crookston, Minn. (**1906**: 884); Ransom County, N. Dak. (**1906**: 976, 979, 984); Carrington, N. Dak. (**1905**: 935, 936); North Platte, Nebr. (**1907**: 823–824, 830); Sarpy County, Nebr. (**1905**: 901); Kearney, Nebr. (**1904**: 868); Riley County, Kans. (**1906**: 938); Wichita, Kans. (**1902**: 635, 636); Garden City, Kans. (**1904**: 902–904); Lower Arkansas Valley, Colo. (**1902**: 740–741); Waco, Tex. (**1905**: 579); Vernon, Tex. (**1902**: 372); Corpus Christi, Tex. (Advance Sheets **1908**: Corpus Christi Area, 20); Blackfoot, Idaho (**1903**: 1035); Minidoka, Idaho (**1907**: 915–916, 917, 919, 921); Salt Lake Valley, Utah (**1899**: 101); Provo, Utah (**1903**: 1127, 1128–1129); Pecos Valley, N. Mex. (**1899**: 62–63); Solomonsville, Ariz. (**1903**: 1059); Salt River Valley, Ariz. (**1900**: 294); Yuma, Ariz. (**1902**: 781–782; **1904**: 1029); Imperial, Cal. (**1901**: 592; **1903**: 1235); Indio, Cal. (**1903**: 1253); San Luis Valley, Cal. (**1903**: 1104); Ventura County, Cal. (**1901**: 528, 538); Los Angeles, Cal. (**1903**: 1269, 1270, 1272); and Santa Ana, Cal. (**1900**: 390).

[a] Cf. Cornish—Geog. jour. **15**: 29–30 (1900).

inside the limiting mountains until it overtopped them;[a] to fill up bordering water courses; or to slowly encroach on a vegetal border. If the winds were insufficiently constant this would not take place, as the accumulations of one storm would be swept away in another direction by the next. Also, if the mountains were too high, or the bodies of water too wide or too deep (as, e. g., the sea), or swift enough to remove the sand as rapidly as delivered,[b] the barrier might never be surpassed. A vegetal border is just as difficult to overcome, for vegetation tends to encroach on the sand plain as much as the plain tends to encroach on the vegetation, and to decide whether the plants will tie down the sand or the sand overwhelm the plants there is always a struggle, the outcome of which is largely dependent on the climatic factors which control the rapidity and vigor of vegetal growth. Those sand wastes of Central Asia which were once vegetation-covered and populous seem to have been invaded by the sand only after the death of the vegetation consequent upon increased aridity.[c]

SAND DUNES.

On areas of loose sand there soon develop by the action of the eolian agencies themselves, hills or ridges of sand—the "dunes"—concerning the formation and structure of which much has been said and written.[d] Dunes are of many forms, which they owe to many

[a] For an example of mountains nearly covered by drifting sand, see Hornaday—Campfires on desert and lava, pp. 347–348 (1908); cf. also p. 162. If there are gaps in the mountains the sand may be driven through to form wide fan-shaped plains—the so-called "sand glaciers." For descriptions of these, see: Stelzner—Geologie argentinischen Rep., vol. **1**, p. 292 (1876); C. W. Thompson—The Atlantic, pp. 289–291 (1878); King, quoted by Pumpelly—Amer. jour. sci. (3) **17**: 139, footnote (1879); Brackebusch—Peterm. Mitth. **39**: 156 (1893); Cornish—Geog. jour. **9**: 286 (1897); Philippi- Ber. deut. Südpolar Exped., Fahrt von Kiel bis Kapstadt, p. 28 (1902), and Zs. deut. geol. Ges. **56**: Monatsb.: 65 (1904); Hume—Cairo sci. jour. **2**: 318 (1908).

[b] For an example (near Gaza in Palestine) of the stoppage of a dune by a small creek, see note by Hull—Geog. jour. **9**: 303 (1897). See also Albert—Actas Soc. cient. Chile **10**: 186 (1900).

[c] Huntington—Pulse of Asia, especially pp. 188–189 (1907).

[d] For general discussions of dunes and dune formation, see Reclus—Bull. Soc. géog. France (5) **9**: 193–221 (1865), The Ocean (English ed.), vol. **1**, p. 198–214 (1873); Günther—Geophysik, vol. **2**, p. 616–619 (1885); Bouthillier de Beaumont—Arch. sci. phys. nat. Geneva (3) **16**: 383–386 (1886); Sokolov—Die Dünen, Bildung, Entwicklung und innerer Bau, 1894; Penck—Morph. der Erdoberfläche, vol. **2**, p. 38–50 (1894); Cornish—Rept. Brit. assoc. **1896**: 857; Geog. jour. **9**: 278–309 (1897), and other papers cited in the bibliography; Bertololy—Kräuselungsmarken und Dünen, 1900; Baschin—Centbl. Bauverwaltung **20**: 231–232 (1900); Richthofen—Führer für Forschungsreisende, p. 345–352, 432–442 (1901); Toula—Deut. Runds. Geog. Stat. **14**: 12–19 (1892); Foureau—Documents scientifiques mission saharienne, vol. **1**, p. 213–237 (1904); Walther—Wüstenbildung, chap. 11 (1900); Jentzsch—Gerhardt's Handbuch deut. Dünenbaues, p. 1–124 (1900), Schrift. naturf. Ges. Danzig (n. s.) **11**: lxi–lxiii (1904); Cholnoky—Földtani Közlöny **32**: 106–143 (1902). Many more special works are cited elsewhere. Résumés of dune science are given in all the major text-books of geology. Some unimportant experiments on dune formation are reported by Courty—La Nature, **31, I**: 211 (1903).

and variable factors, but the initial impulse to dune formation is, in most cases, furnished by some relatively fixed obstacle in the plain of drifting sand. These obstacles may be rocks, buildings, etc., but they are more likely to be simply clumps of vegetation, which collect and hold the sand in the manner already described.[a] If the supply of sand be plentiful, the sand heap soon outgrows and kills the vegetation to which it owes its origin and becomes itself an "obstacle" about which still more sand will accumulate. An isolated heap of this sort on an open plain, and free from the disturbing effects of other dunes, irregular topography, etc., may be considered a typical or normal dune, though the natural forms are usually far more complex. Under the influence of a wind sensibly constant in direction and velocity, such a simple dune exhibits the action of principles which apply to all dunes and which when once discovered can readily be applied to forms of greater complexity.

The collection of sand into a dune does not mean that it has lost its proclivity to drift, for, unless fixed, the dune itself moves more or less rapidly in the direction of the prevailing wind.[b] The sand grains are drifted up the windward side and fall over the crest and down the lee side, and the dune is thus quite literally rolled over and over across the plain. The rate of advance depends on the amount of moving sand,[c] the frequency and violence of the effective winds, and to some extent on the topography of the country. The smaller dunes always move faster. Wesseley[d] observed

[a] On the formation of dunes behind obstacles, see Ehrenberg—Abh. K. Preuss. Akad. Wiss. Berlin **1827**: 73–88; Reade—Geol. mag. (2) **2**: 587–588 (1875); Borggreve—Verh. naturh. Ver. Rheinl. Westf. **32**: Cor.-bl.: 69–72 (1875); Schirmer—Le Sahara, p. 157–158 (1893); Webber—Science (n. s.) **8**: 658–659 (1898); Bertololy—Kräuselungsmarken und Dünen, p. 121–123, 129–130, 134–135 (1900); Walther—Wüstenbildung, p. 122–124, 128 (1900); Reinke—Sitzungsb. K. preuss. Akad. Wiss. Berlin **1903**: 281–295; Foureau—Documents scientifiques mission saharienne, vol. **1**, p. 222–223 (1903); Williams—Iowa Geol. surv. **16**: 462, 490–491 (1905); Gessert—Naturw. Wochens. **21**: 525 (1906); Günther—Sitzungsb. K. Bay. Akad. Wiss. Munich **1907**: 144 et seq.; Beadnell—An Egyptian oasis, p. 83 (1909); and the authorities on the accumulation of sand by vegetation cited in note *b*, p. 50. Cholnoky does not believe that dune formation is initiated by obstacles (Földtani Közlöny **32**: 136 [1902]).

[b] The "prevailing wind" here is really the wind which prevails during the dry season, or in general when the sand of the dunes is in condition for movement. This is, of course, not necessarily the same as the prevailing wind for the whole year. Wesseley—Flugsand, p. 52 (1873). See also note *a* on page 60 of this bulletin, and Gruner—Erl. geol. Spez.-Karte Preuss., Lief. **68**, Bl. Wilsnack, p. 17 (1896); Lehmann—Jahresber. Geog. Ges. Greifswald **10**: 371 (1905); Barron—Topography between Cairo and Suez, p. 117–118 (1907); J. H. Pratt—Jour. Elisha Mitchell sci. soc. **24**: 128 (1908); and Bowman—Bull. Amer. geog. soc. **41**: 150 (1909).

[c] And to some extent on its properties, especially its moisture content.

[d] Flugsand, p. 61 (1873).

a movement of 7 feet a year on the Hungarian sand plains. Among the coastal dunes of north Europe velocities of from 3 to 24 feet a year are cited by A. Geikie;[a] 7 to 30 feet by Wesseley;[b] 1 to 17 feet by Wahnschaffe,[c] 50 feet by Fisher,[d] 20 feet by Lehmann,[e] 18 feet by Berendt,[f] etc. The Gascon coastal dunes move inland 6 to 7½ feet a year according to Brémontier,[g] 62 to 75 feet a year according to Élie de Beaumont,[h] 14 feet a year according to Bagneris,[i] 16½ feet a year according to Marsh,[j] and 33 feet a year according to Bert.[k] According to Cobb[l] a large crescentic dune on the Currituck Banks, North Carolina, has been moving at an average rate of 200 feet a year for twenty years. Halligan[m] records 60 feet a year on the coast of New South Wales. Braine's[n] careful measurements of the rate of advance of South African coastal dunes gave values ranging from zero to over 300 feet a year. In several cases the same dune advanced at different rates at different parts of the crest.[o] The average advance for the locality is probably between 50 and 80 feet a year. Olsson-Seffer[p] observed an advance of 42 feet in one year by some dunes at Veracruz, Mexico, Albert[q] gives the yearly advance of the Chilean dunes as in some places over a thousand feet, and Élie de Beaumont[r] notes a dune on the coast of Brittany which advanced at the rate of 1,762 feet a year. According to Walther[s] velocities of 65 feet a day can be attained by dunes in the Kizyl-kum desert, though the average in this locality is but 20 feet a year.

In the desert between the Jaxartes and the Oxus the dunes move 40 feet northward during the winter, but in the summer the prevailing

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[a] Text-book, vol. 1, p. 443 (1903).

[b] Loc. cit.

[c] Ursachen der Oberflächengestaltung, etc., p. 256–258 (1901).

[d] Forest Protection (Schlich), p. 525 (1895).

[e] Zs. Ges. Erdk. Berlin **19**: 374 (1884).

[f] Zs. deut. geol. Ges. **22**: 173–180 (1870).

[g] Quoted by Czerny—Peterm. Mitth. Ergänzungsh. **48**: 28 (1876)

[h] Leçons de géologie pratique, vol. 1, p. 208 (1847).

[i] Manual de Sylviculture, p. 300 (1878).

[j] The earth as modified by human action, ed. of 1885, p. 564.

[k] Les Dunes de Gascogne, p. 7 (1900).

[l] Jour. Elisha Mitchell sci. soc. **22**: 18 (1906).

[m] Proc. Linn. soc. New South Wales **31**: 632 (1906).

[n] Proc. Inst. civ. eng. **150**: 389–390 (1902).

[o] Similar irregularities have been observed by many investigators. Cf. Berendt—Geologie des Kurischen Haffes, p. 214 (1868); Gottfriedt—Korrespbl. Naturforscherver. Riga **21**: 113–120 (1875).

[p] Jour. geol. **16**: 563 (1908).

[q] Actas Soc. cient. Chile **10**: 315 (1900).

[r] Leçons de géologie pratique, vol 1, p. 202–204 (1847).

[s] Wüstenbildung, p. 119 (1900).

winds are in the opposite direction and the dunes move 60 feet southward, the net result being a southward movement of 20 feet a year.[a]

The result of the process of migration is that dunes tend to form comparatively gentle slopes toward the wind (where the sand is blown up) and steep ones to leeward, where the sand has fallen over the crest. In the ideal case the leeward slope has that angle at which the sand will just remain at rest—usually about 30°– though slightly greater slopes are occasionally found.[b]

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[a] Walther—Wüstenbildung, p. 122 (1900). A similar case has been observed in the Kaveri delta, India, by Wm. King and R. B. Foote—Mem. Geol. surv. India **4**: 251 (1865). On the migration of dunes see also Jordan—Die geographische Resultate der von G. Rohlfs geführten Expedition in die libysche Wüste, p. 26 (1875); Bu Derba—Zs. allg. Erdk. n. s. **8**: 473 (1860); Lenz—Timbuktu, vol. **2**, p. 58 (1880); Keilhack—Jahrb. K. Preuss. geol. Landesanst. **1896**: 194–198; Bertololy—Kräuselungsmarken und Dünen, pp. 161–172 (1900); Gerhardt—Handbuch deut. Dünenbaues, pp. 130–170 (1900); Baschin—Zs. Ges. Erdk. Berlin **1903**: 423–425; Hedin—Scientific results, vol. **2**, pp. 402–409 (1905); Beadnell—An Egyptian oasis, p. 203 (1909); Geog. jour. **35**: 389–391 (1910); and especially the many data collected by Ivchenko—Ann. géol. min. Russ. **9**, I: 244–254 (1908).

[b] The slopes of 60° to 80° reported by Meyen (Reise der Prinzess Louise, vol. **2**, p. 43), Walther (Einleitung in der Geologie als historische Wissenschaft, pp. 792, 794), Engler (Naturw. Wochens **17**: 278 [1902]), and other writers are almost certainly due to errors of observation; the great probability of which has been pointed out by Cholnoky (Földtani Közlöny **32**: 108–109 [1902]). Slopes as steep as these are impossible for dry sand, and in fact the reports of slopes of 40° and over are much open to suspicion, though such slopes may be formed in cases where the sand is moist or otherwise cemented and has been eroded by undercutting. For instances see Baschin—Zs. Ges. Erdk. Berlin **1903**: 428; Hedin—Scientific results, vol. **1**, pp. 121–122 (1904). These can not be considered dune slopes. On the other hand, the maximum of 23° to 24° given by Chamberlin and Salisbury (Geology, vol. **1**, p. 27) is certainly too low for moving dunes.

The following measurements are found in the literature:

Cape Henry, Virginia: 45°, Kearney—Contrib. U. S. nat. herb. **5**: 334 (1901).

Cape Hatteras, North Carolina; 35°, Bond—Jour. Elisha Mitchell sci. soc. **24**: 132 (1908).

Clatsop Beach, Oregon; 40°, Diller—Ann. rept. U. S. Geol. surv. **17**, I: 456 (1896).

Dune Park, Michigan; 30°, Cowles—Bot. gaz. **27**: 191 (1899).

Gascon Coast; 29° to 30°, Reclus—La terre, vol. **2**: p. 239 (1868); 32° to 40°, Walther—Einleitung in der Geologie als historische Wissenschaft, p. 845 (1894).

North German Coast; 45°, Berendt—Schrift phys. ökon. Ges. Königsberg **9**: 140 (1868); 41° (maximum), Hagen—Handbuch Wasserbaukunst **3**: 149–172 (1863).

Denmark; 30° (average), Forchhammer—Neues Jahrb. Min. **1841**: 2, 6.

Island of Sylt; 33°, Baschin—Zs. Ges. Erdk. Berlin **1903**: 429.

Hungary; 27° to 32° (average 30°), Wesseley—Flugsand, pp. 27, 28, 54 (1873); 34.5°, Cholnoky—Földtani Közlöny **32**: 108 (1902). (This is the greatest slope ever observed by this author.)

Kharga, Egypt; 30° to 33°, Beadnell—An Egyptian oasis, p. 203 (1909).

Capetown, South Africa; 30° (average), maximum is 32°, Braine—Proc. Inst. civ. eng. **150**: 387 (1902).

Turkestan 30° to 40°, Mushketov—Nature **34**: 237 (1886).

Tarim Basin; 26° to 39° (many measurements, mostly between 31° and 33°), Hedin—Through Asia, vol. **2**: p. 790 (1899); Peterm. Mitt. Ergänzungsh. **131**:

The crescentic shape frequently observed in isolated dunes has been similarly explained. The sand is blown around the ends and stretches out in long points to leeward, forming a more or less perfect

FIG. 1.—Group of crescentic dunes in the desert near Bokhara (after Walther).

crescent. Plate I, figure 2, shows a typical dune of this form in the delta of Carrizo Creek in the Colorado Desert, and figure 1 (after

243–244 (1900); Central Asia and Tibet, vol. **1**: pp. 247, 264, 268, 272 (1903); Scientific results, vol. **1**: p. 270 (1904).

Transcaspian Desert; 30° to 40°, Radde—Peterm. Mitt. Ergänzungsh. **126**: 11–12 (1898).

South Australian Coast (?); 36° (maximum), Wilkinson—Jour. & Proc. Roy. soc. N. S. Wales **16**: 94 (1882).

The following measurements have been made by the present writer: Gypsum dunes of the Alamogordo Desert, 32°, 32.6°, 33°, 34°; crescentic dunes of the Carrioz

Walther) shows a bird's-eye view of a group of such dunes in the Trans-Caspian Desert. Dunes of this form are found in nature only where the winds blow mostly in one direction and where the dunes are not interfered with by the topography of the country or by each other. In most cases the typical form is variously modified and obscured. Characteristic examples have, however, been observed in many localities; as, for instance, in Arabia by Wellsted,[a] Lady Blunt [b] and Euting; [c] in the central and west Asian deserts by Burnes,[d] Forsyth,[e] Middendorff,[f] MacGregor,[g] Mushketov,[h] Lóczy,[i] Walther,[j] Rein,[k] Radde,[l] Hedin,[m] Cholnoky,[n] Ivchenko,[o] McMahon,[p] Davis,[q] Pompeckj,[r] and Stein;[s] and in the Sahara by Nachtigal,[t] and

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Creek delta, Colorado Desert, 31.5°, 31.8°, 31.9°, 32°; dune southwest of Fallon, Nev., 31°; dune area south of Las Animas, Colo. (Arkansas Valley), 32°, 32.3°; littoral dune at Hermosa, Cal. (near Los Angeles), 31°, 33.5°; coastal dune area southwest of San Francisco, Cal., 31°, 31.1°, 31.5°, 31.6°.

The angles of rest of various dry pulverulent materials have been investigated experimentally by Auerbach (Ann. Phys. (4) **5**: 170–219 [1901]), who found (p. 180), for the four kinds of sand examined, values ranging from 34.2° to 35.8°. The angles of rest of the dry sand dunes which were being undercut by the Tarim River (Eastern Turkestan) were measured by Hedin as from 32° to 34° (Scientific results, vol. **1**: p. 167 [1904]). A similar slope on the dune lands southwest of San Francisco, Cal., was measured by the present writer as 31.2°.

The lee slope of crescentic dunes of granular snow at Winnipeg, Canada, was measured by Cornish (Geog. jour. **20**: 151 [1902]) as 30°. The angles of rest (and resultant slopes) of the volcanic lapilli and scoria of the cinder cone at Lassen Peak, Oregon, vary from 30° to 37° according to the size of the material (Diller—U. S. Geol. surv. Bull. **79**: 11 [1891]).

[a] Travels in Arabia, vol. **1**, p. 411 (1838).

[b] A Pilgrimage to Nejd, vol. **2**, p. 242–243 (1881).

[c] Verh. Ges. Erdk. Berlin **13**: 267 (1886).

[d] Travels into Bokhara, vol. **3**, p. 1–2 (1834).

[e] Jour. Roy. Geog. soc. **47**: 9 (1877).

[f] Mém. Acad. imp. sci. St. Petersburg **29**: 29 (1881).

[g] Wanderings in Baluchistan, p. —— (1882). These same dunes were later visited by McMahon, who observed no change of form. (Geog. jour. **9**: 309 [1897]).

[h] Nature **34**: 237 (1886), Földtani Közlöny **17**: 269–275 (1887), Deut. Rund. Geog. Stat. **12**: 149 (1890).

[i] Reise Grafen Széchenyi in Ostasien, vol. **1**, p. 506 (1893).

[j] Bull. Soc. imp. nat. Moscow (n. s.) **11**: 437–445 (1897); Peterm. Mitt. **44**: 207–208 (1898); Wüstenbildung, p. 123 (1900). These dunes are shown in fig. 1, p. 61.

[k] Ber. senckenb. naturf. Ges. **1898**: cxxiv.

[l] Peterm. Mitt. Ergänzungsh. **126**: 11–12 (1898).

[m] Through Asia, vol. **1**, p. 488, 492, vol. **2**, p. 789–790 (1899); Peterm. Mitt. Ergänzungsh. **131**: 238 (1900); Scientific Results, vol. **1**, p. 232 (1904).

[n] Földtani Közlöny **32**: 106 (1902).

[o] Ann. géol. min. Russie **7**, I: 51–54, 226–229 (1904); **8**: 135–188 (1906).

[p] Geog. jour. **28**: 337 (1906). See also note (in discussion) ibid. **9**: 306 (1897).

[q] Carnegie Inst. of Washington Pub. **26**: 42, 44, 57 (1905).

[r] Centbl. Min. **1906**: 373–378.

[s] Ancient Khotan, p. 242 (1907).

[t] Sahârâ und Sûdân, vol. **2**, p. 68 (1881).

by Rolland;[a] in India by Oldham;[b] in the Gascon "landes" by Grandjean[c] and Buffault;[d] near Dresden by Gutbier;[e] on the west coast of Africa by Gentz;[f] in East Africa by Gessert;[g] in Chile by Meyen;[h] in Peru by Pöppig,[i] Tschudi,[j] Bollaert,[k] Abercromby,[l] Douglass,[m] Sears,[n] and S. I. Bailey;[o] in the Colorado Desert by Holmes,[p] MacDougal,[q] and Tolman;[r] at Rufus, Oregon (along the Columbia River) by Westgate[s] and the writer; on the Hatteras Banks by Cobb,[t] etc.[u]

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[a] Bull. Soc. géol. France (3) **9**: 508–551 (1881), **10**: 30–47 (1882). See also Rolland—Géologie du Sahara algérien, plate 23, fig. 5 (1890).

[b] Jour. Asiat. soc. Bengal **45**, II: 102 (1876); Mem. Geol. surv. India **34**: 141–148 (1903).

[c] Bull. Soc. géog. comm. Bordeaux (2) **19**: 184 (1896).

[d] Étude sur la côte et les dunes de Médoc, p. 95 (1897). See also Marsh—The earth as modified by human action, ed. of 1885, p. 540. On other crescentic coastal dunes see Jentzsch—Gerhardt's Dünenbaues, pp. 87–88 (1900); and Baschin—Zs. Ges. Erdk. Berlin **1903**: 422–428.

[e] Sitzungsb. Isis Dresden **1864**: 42–54. On the fossil crescentic dunes of the German heaths see Solger—Zs. deut. geol. Ges. **57**, Monatsb.: 179–190 (1905); but see p. 64, below.

[f] Deut. Kol. Ztg. **19**: 93–94 (1902).

[g] Naturw. Wochens. **21**: 525 (1906).

[h] Reise der Prinzess Louise, vol. **2**, p. 43 (1835).

[i] Reise in Chile, Peru und auf dem Amazonenstrome, vol. **1**, pp. 140–142 (1835).

[j] Peru, Reiseskizzen, vol. **1**, p. 336 (1846).

[k] Jour. Roy. geog. soc. **21**: 99–129 (1851).

[l] Quart. jour. Roy. meteor. soc. **16**: 120 (1890).

[m] El Kosmos (Arequipa, Peru) no. 21, Dec. 30, 1892; Appalachia **12**: 34–45 (1909).

[n] Bull. Amer. geog. soc. **27**: 262 (1895).

[o] Ann. Astron. obs. Harv. coll. **39**: 287–292 (1906).

[p] Field Operations, Bureau of Soils **1903**: 1235.

[q] Bull. Amer. geog. soc. **39**: 708 (1907); Botanical features of North American deserts, p. 38 (1908).

[r] The Crescentic dunes of the Salton Sea. These dunes were visited in June, 1909, by Dr. B. E. Livingston and the writer, who found conditions practically unchanged since Tolman's visit.

[s] Unpublished observations.

[t] Jour. Elisha Mitchell sci. soc. **22**: 17–19 (1906).

[u] These dunes are often called "barchans." On their general nature and formation see Cornish—Geog. jour. **9**: 278–309 (1897); Oldham—Loc. cit. supra; Mushketov—Deut. Runds. Geog. Stat. **12**: 148 (1890); Cholnoky—Földtani Közlöny **32**: 111–123 (1902). Crescentic dunes of drifting snow have been described by Cornish—Geog. jour. **20**: 151 (1902); Cholnoky—loc. cit., p.116; Ferrar—National Antarctic exped. 1901–4, Nat. hist. **1**: 84 (1907); von Staff—Zs. deut. öster. Alpenver. **37**: 49 (1906), and Tschirwinsky—Zs. Gletscherk. **2**: 104–112 (1907). Quite analogous crescentic forms are sometimes formed from loose sand or gravel under flowing water. The author has seen them on sand-sprinkled street pavements over which a thin sheet of rain water was flowing. Cornish has observed them in beach shingle (Geog. jour. **11**: 639 [1898]). The author observed at Fallon, Nev., in July, 1909, a dune of crescentic shape almost entirely fixed by vegetation. It is impossible to say

A common variation of the crescentic form is that produced by the joining of two or more adjacent dunes as they increase in size. Several good examples are shown in fig. 1, where at *a* two dunes, and at *b* three dunes have joined. At *c* are three other dunes which are likely soon to do so. If only two or three dunes join, the final result is usually simply a larger dune of the crescentic form,[a] but if the number of joining dunes is large, there is a tendency to produce more or less irregular forms of great complexity. Sometimes, either by the union of isolated dunes or possibly in other ways, there will be formed long and passably straight ridges transverse to the ruling wind direction and frequently in series parallel to each other, like huge ripple systems. Such transverse ridges are similar to isolated dunes in their proclivity to migration, in their slope relations, etc.

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whether this is a barchan which has been grown over with plants or whether the crescentic form is accidental.

Mention should perhaps be made of the unusual crescentic dunes whose points face the wind instead of stretching to leeward. These occur on certain coasts and are generally believed to be formed by the lag of the flanks of an ordinary rounded dune as it moves forward. The sand at the edges of the dune being thinner, is believed to be more easily fixed by vegetation or held by ground water rising from below. The central higher part is therefore the more free to move, and gradually leaves the flanks behind. This hypothesis explains the occurrence of such dunes mainly on coasts, for it is exactly here that strong winds are combined with a relatively strong tendency toward fixation of the sand. On these dunes see Sokolov—Die Dünen, pp. 97 et seq. (1894); Bertololy—Kraüselungsmarken und Dünen, pp. 144–145 (1900); Jentzsch—Gerhardt's Dünenbaues, p. 87 (1900); Cholnoky—Földtani Közlöny **32**: 123–125 (1902); Lehmann—Zs. deut. geol. Ges. **57**, Monatsb.: 264–265 (1905), Jahresb. Geog. Ges. Greifswald **10**: 351–379 (1905). Dr. W J McGee tells me that he has observed many instances among the dunes of western Nebraska. I have myself observed one on the Pacific coast near San Francisco. The fossil crescentic dunes of Galicia and of north Germany may be of this type. See Friedberg—Atlas geol. Galicyi **16**: 33–37 (1903); Solger—Zs. deut. geol. Ges. **57**, Monatsb.: 184–185 (1905), Verh. deut. Geographentags (Danzig) **15**: 159–172 (1905), Monatsb. deut. geol. Ges. **1908**: 54–59; Romer—Kosmos (Lwów) **31**: 10–12, 334–362 (1906); Verh. geol. Reichsanst. **1907**: 48–55; Jentzsch—Monatsb. deut. geol. Ges. **1908**: 120–123. Solger's last article (loc. cit.) points out important differences between these reversed crescentic dunes (or "parabolic dunes") and the typical barchans.

It is, of course, possible that some observations of crescentic dunes whose points face the wind may be in error, due to the dunes having been observed during a wind contrary in direction to that by which they had been formed. For a case of this sort (Meyen and Pöppig on the South American dunes) see Bertololy, loc. cit., p. 153. Barchans are, however, very sensitive to changes in wind direction and are rapidly modified in form by a reversed wind. See Hedin—Geog. jour. **8**: 361 (1896); Walther—Bull. Soc. imp. nat. Moscow n. s. **11**: 443–445 (1897); Baschin—Zs. Ges. Erdk. Berlin **1903**: 427–428 (1903); Hedin—Scientific results, vol. **1**, p. 277–278 (1904); Beadnell—An Egyptian oasis, p. 205 (1909).

[a] A dune in which this process is almost complete is shown at *d* in fig. 1. On the union of crescentic dunes see also Hedin—Scientific results, vol. **1**, pp. 351–354 (1904).

They are frequently to be found in deserts [a] and are responsible for the well-known wave-like surface of these areas. Coastal dunes are also usually linear and transverse to the prevailing wind, but are not so likely to be regular in form as are the ridges of the desert, being largely determined by the shape of the coast line, the amount of sand supplied at various points, etc.

In addition to these forms, all of which have their greatest extension in a direction transverse to the wind, there are also dunes which stretch out parallel thereto. The precise nature of the processes which give rise to these longitudinal dunes is very uncertain, but such forms seem to occur most readily where the supply of sand is small relative to the strength of the wind.[b] Where more sand is available (or the wind less regnant) the dunes are transverse.

The brief discussion of dunes above given is based on the theories of dune formation which find general acceptance at present.[c] It is possible, however, that too little stress has been laid upon the effect

[a] For instance in India see Strahan—Gen. Rept. Surv. India dept. **1882–83**, App.: 3–4. (Cf. also Note *b* below). In Central Asia: Hedin—Through Asia, vol. **1**, p. 499, vol. **2**, pp. 777, 791 (1899), Peterm. Mitth. Ergänzungsh. **131**: 245 (1900); P. M. Sykes—Geog. jour. **19**: 161 (1902). In Arabia: Wellsted—Travels in Arabia, vol. **1**, pp. 86–87 (1838); Palgrave—Narrative of journey through Arabia, p. 62 (1865); Phillips—Quart. jour. Geol. soc. **38**: 110 (1882); Zwemer—Geog. jour. **19**: 61 (1902). In the Sahara: Tristram—The great Sahara, pp. 300–302 (1860); Choisy—Documents Mission Algérie, p. 323 (1890); Rolland—Bull. Soc. géol. France (3) **10**: 30 (1882). In Australia: Sturt—Central Australia, vol. **1**, pp. 183–186, 233, 251, 336, 338–339, 371, 379, 380, 405 (1848), vol. **2**, pp. 26, 33–36, 42, 45 (1849); Carnegie—Spinifex and sand, pp. 178, 249–252, 377 (1898). It appears, however, that these often-cited Australian ridges are composed not really of sand, but of "loam" covered with sand. See Sturt, loc. cit., vol. **1**, p. 379, and Gregory—Dead heart of Australia, pp. 65, 109 (1906). Their true nature and origin remain in doubt. Transverse ridges of drifted snow occur in the arctic regions. See, e. g., Wrangell—Narrative, p. 244 (1840).

[b] On the nature and formation of longitudinal dunes see Blanford—Jour. Asiat. soc. Bengal **45**, II: 92–93, 97–103 (1876); Medlicott and Blanford—Geology of India, 2d ed. (Oldham), p. 455 et seq. (1893); Cornish—Geog. jour. **9**: 292–293 (1897), **20**: 153, 160 (1902); Blake—Quart. jour. Geol. soc. **53**: 228–229 (1897); Beadnell—Geol. jour. **35**: 380 et al. (1910). It is possible the longitudinal dunes may be formed by the erosion of the troughs rather than by accumulation (see Cholnoky—Földtani Közlöny **32**: 141 [1902]). This is probably true of the longitudinal snow dunes of arctic and antarctic latitudes (Philippi—Zs. deut. geol. Ges. **56**, Monatsb. 66 [1904].) The first stage of the dune of accumulation is, however, longitudinal, and consists simply of a long tongue of sand stretched out behind the inducing obstacle. See Bertololy—Kräuselungsmarken und Dünen, pp. 129–130 (1900), and cf. Reade—Geol. mag. (2) **2**: 587–588 (1875); and Günther—Sitzungsb. K. Bay. Akad. Wiss. Munich **1907**: 139–153.

[c] The best discussions are the excellent articles of Cornish (Geog. jour. **9**: 278–309 [1897]), and of Cholnoky (Földtani Közlöny **32**: 106–143 [1902]). See also the works cited on page 57 above and elsewhere in this chapter.

of the eddy behind the dune in determining or modifying its structure.[a] The nature of the eddy thus produced is indicated by the diagram, figure 2 (after Darwin), where the directions of the moving air are indicated by the stream lines and arrows. This back eddy not only blows sand up the lee slope, thus maintaining or even increasing its steepness, but it is also active in excavating and keeping clear the trenches between the dunes of a dune complex.[b] The action becomes apparent to the eye when the crest of a dune forms the sky line, for there is then seen, rising from the crest, a thin stream of "dune smoke,"[c] which is undoubtedly simply sand blown upward by the current produced at the meeting point of the eddy and the main wind. It is probable that this eddy, perhaps in modified form, is responsible for the crater-shaped hollows occasionally found at the tops of large dunes,[d] and perhaps for other anomalies of dune structure.

FIG. 2—Ideal diagrams of air currents showing tendency of wind to blow sand up ridges in both directions (after Darwin).

[a] See, however, Cornish—Geog. jour. **15**: 7, 22, 23 (1900); Bertololy—Kräuselungsmarken und Dünen, pp. 137–139 (1900); Hedin—Scientific results, vol. 1, pp. 246–250 (1904); and Lomas—Trans. Liverpool geol. soc. **10**: 187 (1905–6).

[b] The action of heavy winds in excavating these troughs has been noticed among the Gascon dunes by Grandjean—Bull. Soc. géog. comm. Bordeaux (2) **19**: 183–184 (1896). Similarly Foureau (Documents scientifiques mission saharienne, vol. 1, p. 236–237 [1904]) has noticed that the troughs between the Sahara dunes do not tend to fill up, but that the materials of the (presumably) original surface can still be seen at their bottoms. Hedin has observed similar conditions in some of the troughs between dunes in the Takla-makan desert (Through Asia, vol. 1, pp. 457, 472 [1899]; Peterm. Mitth. Ergänzungsh. **131**: 243, 244 [1900]; Central Asia and Tibet, vol. 1, pp. 268, 279 [1903]; and especially, Scientific results, vol. 1, pp. 246–250, 413 [1904]).

[c] Marès—Ann. Soc. météor. Paris **12**: 284–289 (1864); Zittel—Peterm. Mitt. **20**: 185 (1874); Grandjean—Bull. Soc. géog. comm. Bordeaux (2) **19**: 182 (1896); Albert—Actas Soc. cient. Chile **10**: 171 (1900); Hedin—Through Asia, vol. 1, p. 516 (1899); Central Asia and Tibet, vol. 1, p. 272 (1903); Stein—Sand-buried ruins of Khotan, p. 429 (1903); Beadnell—Geog. jour. **35**: 387 (1910).

[d] My attention was first called to this phenomenon by Dr. W J McGee, who has observed that the most lofty (and therefore most exposed) dune of any complex frequently has on its summit a hollow surrounded on all sides by a raised rim. Similar hollows have been observed in the Capetown dunes by Braine (Proc. Inst. civ. engs. **150**: 387 [1902]), in the dunes at Mogador (Moroccan coast) by Maw (Hooker and Ball's Morocco and the Great Atlas, p. 453 [1878]), and on the English coast by Shone (loc. cit. infra). Hedin observed among the dunes of the Takla-makan desert circular hollows which he believed due to the meeting of two crescentic dunes, facing in opposite directions (Through Asia, vol. 2, p. 828 [1899]; Peterm. Mitth. Ergänzungsh. **131**: 238, 243 [1900]). Cf. also Reclus—Bull. Soc. géog. France (5) **9**: 205–206 (1865); Mushketov—Deut. Runds. Geog. Stat. **12**: 149 (1890); Cholnoky—Földtani Közlöny

The actual forms of natural dunes are of course exceedingly complex, expressing in any individual case the resultant of many and ever-varying factors, of which the degree of constancy in the direction of the wind is doubtless the most important, and next to this the relation between the amount of available sand and the wind velocity. The topography of the underlying surface is also important and the physical properties of the sand are not without influence.[a]

WIND-FORMED SAND RIPPLES.

Among the most interesting of the minor phenomena of sand-drift is the formation of the systems of superficial ripples which are frequently produced on smooth surfaces of drifting sand,[b] and which resemble the ripples that occur on the sandy bottoms of streams or on sandy beaches. The mechanism of ripple formation is not perfectly clear, and it is not improbable that in this case, as in so many others, forms apparently the same may result from quite dissimilar causes. The formation of the typical eolian ripples is, however, probably connected with the tendency of all moving fluids to take on a sinusoidal

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32: 138 (1902); Beadnell—Geog. jour. **35**: 387 (1910). It is easier to imagine these formed by eddies, and in any case they must be kept open by this means if they are to endure. Brunhes, following out his theories of the importance of erosion by whirlwinds, considers isolated circular hollows among dunes as formed in this way (Mem. Accad. Nuovi Lincei (5) **21**: 129–148 [1903]). While this may be true in certain cases, it seems hard to imagine the circumtances under wnich a vertical eddy would be regularly produced on the *top* of a high and approximately conical dune. On the other hand, it is easy to see that the top of such a dune might be hollowed out by the horizontal eddies set up by winds blowing up the dune slope from different directions at different times. It may be, as suggested by Shone (Geol. Mag. (3) **10**: 323 [1893]), that the action of the eddy is sometimes initiated by a slight sinking of the center of the sand heap under the action of rain.

[a] As, for instance, its cohesion. See Günther—Sitzungsb. K. Bay. Akad. Wiss. Munich **1907**: 139–153; and analogous observations on snow dunes by Cornish (Geog. jour. **20**: 153 [1902]).

[b] Maw—Quart. jour. Geol. soc. **28**: 88 (1872); Rae—Nature **29**: 357 (1884); Walther—Denudation in der Wüste, p. 523 (1891); Cornish—Rept. Brit. Assoc. **1896**: 794–795, Geog. jour. **9**: 280 et seq. (1897); Baschin—Zs. Ges. Erdk. Berlin **34**: 408–424 (1899); Hedin—Through Asia, vol. **1**, p. 515, vol. **2**, p. 790 (1899); Bertololy—Kräuselungsmarken und Dünen, pp. 99–105 (1900); Ivchenko—Ann. géol. min. Russie **7**, I: 223–226 (1904), **8**: 140–142 (1906); Joly—Sci. proc. Roy. soc. Dublin (n. s.) **10**: 328–330 (1904); Geinitz—Naturw. Wochens. **19**: 1025–1031 (1904); Hedin—Scientific results, vol. **2**, pp. 410–440 (1905); etc. Eolian ripples in moderately coarse gravel have been described by Richardson—Rept. Yorkshire phil. soc. **1902**: 47; and Oldham—Mem. Geol. surv. India **34**: 141 (1903). Similar ripples occur on drifting snow. See Cornish—Rept. Brit. assoc. **1900**: 816–817, **1901**: 398–399, Scott. geog. mag. **17**: 1–11 (1901), Quart. jour. Geol. soc. **58**, Proc.: ii, iv (1902), Geog. jour. **20**: 137–173 (1902), Quart. Jour. Roy. meteor. soc. **35**: 149–160 (1909); von Staff—Zs. deut. öster. Alpenver. **37**: 45–48 [1906] and Giraud—Geographic **3**: 345–347 (1901).

motion at high velocities.[a] Such a system of regularly recurring eddies in the air would naturally impress itself more or less exactly on the loose sand beneath.[b]

THE PROPERTIES OF BLOWN SANDS.

Drifting sands may be of the most varied materials, ranging from the nearly pure limestone sands of coral-fringed coasts to the quartz sands of equal purity found on some beaches and in the older deserts. Interesting dune areas of nearly pure gypsum sand occur in New Mexico[c] and in Utah.[d] Dunes of clay aggregates are reported from Texas.[e]

In general, the composition of any sand is dependent upon that of the rocks from which it was derived; and since most drifting sands are much mixed and derived from many and varied rocks, they possess, when not too long exposed to the action of the disintegrating agencies, a high degree of qualitative if not quantitative heterogeneity. On long exposure to mechanical disintegration and removal there is, as already described, a tendency for sands to become siliceous, and the remarkable purity of some desert sands[f] is no doubt thus attained. Even in these extreme cases there is usually, however, some slight admixture of other minerals as is shown (amongst other evidence) by the not inconsiderable productivity of the sands when rendered stationary and supplied with water.[g]

In mechanical composition dune sands are somewhat more uniform. As the result of numerous mechanical analyses, Udden[h] concludes

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[a] See the experimental investigations of Reynolds on flowing water (Phil. trans. Roy. soc. **174**: 935–982 [1884]); and the theoretical deductions of Helmholtz (Crelle's Jour. Math. **55**: 25–55 [1858]; Monatsb. K. Preuss. Akad. Wiss. Berlin **1868**: 215–228). In connection with the latter papers see Rayleigh—Proc. London math. soc. **11**: 57 (1880); and Kelvin—Nature **23**: 45–46, 70 (1880). For an observation of sinuosities in natural air currents see Baddeley—Whirlwinds and dust storms in India, p. 52 (1860).

[b] See Baschin—Zs. Ges. Erdk. Berlin **34**: 408–424 (1899); Centbl. Bauverwaltung **20**: 231–232 (1900).

[c] Mentioned by the early explorers. Described by G. Gibbs—Amer. nat. **4**: 695–696 (1870); MacBride—Science (n. s.) **21**: 91 (1905); Brady—Mines and Minerals **25**: 529–530 (1905); and MacDougal—Botanical features of North American deserts, pp. 11–16 (1908).

[d] I. C. Russell—Geol. mag. (3) **6**: 289 (1889).

[e] Coffey, George N.—Jour. geol. **17**: 754–755 (1909).

[f] Walther—Einleitung in Geologie als Historische Wissenschaft, p. 795 (1893–4); Schirmer—Le Sahara, p. 156 (1893); Doss—Korrespbl. Naturforscherver. Riga **39**: 31–40 (1896); Bertololy—Kraußelungsmarken und Dünen, p. 5 (1900), etc.

[g] For details concerning the chemical and mineralogical composition of eolian and other sands see Walther—Einleitung in der Geologie als Historische Wissenschaft, p. 837 (1894); Retgers—Neues Jahrb. Min. **1895**, I: 16–74; Sabban—Mitt. Grossh. Meckl. geol. Landesanst. **8**: 20–52 (1897); Neuber—Deut. Runds. Geog. Stat. **27**: 241–247 (1905); Warren—Tech. quart. **19**: 317–338 (1906).

[h] The mechanical composition of wind deposits, pp. 9–26 (1898).

that most drifting sand is composed of grains ranging in diameter from 0.5 to 0.125 mm.[a] Indeed, the blown sand of any one locality is likely to be even more uniform than this, though sands from different areas will sometimes differ more widely as a result of varying strength of wind, etc. This uniformity is a natural result of the means by which the sands have been collected, and is to be expected in the light of the process of air sorting, as described on pages 35–37. The shape of the grains is largely dependent on the history of the sand. Desert sands formed by insolational disintegration[b] and not much rolled about are angular,[c] while sand grains subjected to much abrasion by either eolian or aqueous transport have the well-known rounded form of stream-worn material.[d] The degree of rounding carries no indication as to the means by which it was produced. If anything, the eolian sand is likely to be the more rounded, for eolian abrasion is just as complete as and probably more rapid than that

[a] This conclusion is in accord with the results of the few mechanical analyses of dune sands which have been made by the Bureau of Soils, and also with the results of analyses cited by Thoulet—Bull. Soc. min. France **4**: 263 (1881); Sabban—Mitt. Groesh. Meckl. geol. Landesanst. **8**: 43–49 (1897); Früh—Vierteljs. naturf. Ges. Zurich **44**: 174–175 (1899); Oldham—Mem. Geol. surv. India **34**: 150 (1903); Galunov—Lĭĕsnoi zhur. **33**: 1217–1224 (1903); Lehmann—Jahresb. geog. Ges. Greifswald **10**: 372 (1905); and Juritz—Trans. South African phil. soc. **18**: 28 (1907). See also Keilhack—Chemztg. **29**: 723 (1905), and Atterberg—ibid. p. 1074 (1905); and Table XII on p. 168 below.

[b] By insolational disintegration is meant the mechanical splitting of rocks and rock fragments due to unequal expansion (especially of the grains of different minerals) under the rapid and intense changes of temperature which occur in the desert. See Fraas—Aus dem Orient, pp. 176–177 (1867); Walther—Denudation in der Wüste, pp. 481–500 (1891), Wüstenbildung, pp. 176–177 (1900); Schirmer—Le Sahara, pp. 143–144 (1893); Obruchev—Verh. Imp. min. Ges. St. Petersburg (2) **33**: 245–249 (1895); Goodchild—Trans. Edinb. geol. soc. **7**: 205–206 (1897); Chamberlin and Salisbury—Geology, vol **1**, pp. 44–48 (1904); Ivchenko—Ann. géol. min. Russ. **7**, I: 45–46 (1904); Barrell—Jour. geol. **16**: 176–179 (1908); and Łoziński—Bull. Intern. acad. sci. Cracow, **1909**: 1–25. Other observations have been made by Wellsted—Travels in Arabia, vol. **2**, p. 79 (1838); Darwin—Journal of researches, ed. of 1901, p. 318; Sturt—Central Australia, vol. **1**, p. 180, 240, 244 (1849); Livingstone—Missionary travels, p. 149 (1857), Zambesi, pp. 429, 516 (1865); Philippi—Viage al Disierto del Atacama, pp. 111–112 (1860); Vatonne, in Mircher—Mission de Ghadamès, pp. 245, 271, 276 (1863); Jordan—Physische Geographie lybischen Wüste, p. 127 (1876); Walther—Verh. Ges. Erdk. Berlin **15**: 249 (1888); Murray—Proc. Roy. geog. soc. (n. s.) **12**: 464–466 (1890); Branner—Bull. Geol. soc. Amer. **7**: 255 (1896); Barron and Hume—Topography and Geology Eastern Desert of Egypt, pp. 285–286 (1902); Stahl—Vegetationsbilder, **2**, Heft 4, Tafel 24 and text (1904); MacDougal—Botanical features North American deserts, pp. 77–79 (1908); Stein—Geog. jour. **34**: 14 (1909), etc.

[c] See, e. g., Walther—Denudation in der Wüste, Plate VII; C. C. Parry—Rept. U. S. Mex. Boundary Surv., vol. **1**, II: p. 10 (1857); Emory—ibid., I: p. 40; La Touche—Mem. Geol. surv. India **35**: 40 (1902); J. Ball—Aswan Cataract of the Nile, p. 64 (1907).

[d] For instances of well-rounded sands in deserts see Blake—Pacific Railway Repts., **2**: 20 (1855), **5**: 119 (1856); Rolland—Rev. sci. (3) **1**: 610 (1881); Phillips—Quart. jour. Geol. soc. **38**: 111 (1882); J. Ball—Aswan Cataract, p. 57, Plate III (1907); etc.

produced under streams or waves.[a] The only difference is that eolian rounding extends to particles so small that they would be unaffected by water transport,[b] and this fact has been used as a proof of the eolian origin of certain loessial deposits, the finest grains of which are well rounded.[c]

The uniformity and coarseness (as compared with soil in general) of drifting sand makes it exceptionally open in texture. It has been shown by Slichter[d] that for spherical grains of uniform size (a condition nearly approached by dune sands) the closest possible arrangement of the grains leaves 25.90 per cent of unoccupied space, while the loosest arrangement leaves 47.64 per cent, regardless of the size of spheres. These percentages of pore space are, however, not large More important is the relatively large size of the individual spaces, which enables water to move into and through dune sands more readily than is the case with more normal soils of less mechanical uniformity. The rates both of absorption and of drainage are greater than in deposits composed of or containing finer material. Reference should be made, however, to the observation of Wesseley,[e] later repeated by Shaler,[f] that *dry* dune sands sometimes offer considerable resistance to the penetration of water. The sand grains become wetted very slowly and the intergranular capillary films are not readily set up. This may occur in certain cases, but it is probably not a property of all sands, and in no case does it apply when water is actually covering the general surface.

Although amply absorptive, sands have little power of retaining moisture. All added water flows at once to lower levels and the amount held by capillary action is far less than in finer materials.[g] The water content of sands above the ground-water level is therefore

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[a] See Sorby—Quart. jour. Geol. soc. **36**, Proc.: 50, 57–61 (1880); Phillips—Quart. jour. Geol. soc. **37**: 6–28 (1881); Klemm—Zs. deut. geol. Ges. **34**: 779 (1882); Goodchild—Trans. Edinb. geol. soc. **7**: 208–211 (1897); Mackie—ibid, pp. 298–311; Bonney—Geog. jour. **9**: 302 (1897); especially Mackie's article.

[b] Daubrée—Géologie expérimentale, pp. 250 et seq. (1867); and Sorby's article cited in last note. Cf. also on the limit of attrition of beach sands, Shaler—Bull. Geol. soc. Amer. **5**: 208 (1894).

[c] See, for instance, Sauer's observations on the Meissner loess (Zs. Naturw. **62**: 330–331 [1889]); and Früh's table of the shape of loess grains (Vierteljahrsch. naturf. Ges. Zurich **44**: 174–175 [1899]).

[d] Ann. Rept. U. S. Geol. Surv. **19**, II: 306 et seq. (1899). Kemna has made the same calculations (Bull. Soc. belge géol. **15**: Proc. verb. 122–128 [1901]). Some actual measurements by Ramann give values of 42.2 to 44.1 as the per cent of pore space in dune sands (Zs. Forst- Jadgw. **30**: 370–371 [1898]).

[e] Flugsand, p. 60, 62 (1873).

[f] Bull. Geol. soc. Amer. **5**: 211 (1894).

[g] See the experiments of Loughridge (Rept. Cal. agr. expt. stat. **1892–4**: 80–100 [1894]), also Bull. **10**, Bur. of Soils, U. S. Dept. of Agr.; and E. J. Köhler—Physikalische Eigenschaften des Sandes, 1906, where further literature is cited.

lower than in normal soils, and this explains the xerophytic character of all dune floras, even in regions of ample rainfall.[a] The overdrainage of sandy lands is, however, partially compensated by the slightness of the evaporational losses to which they are subject. It has been shown by Buckingham[b] in this laboratory that evaporation from all soils takes place almost entirely from the surface, and that the water in the lower layers can be lost by evaporation only by being first raised to the surface by capillary action.[c] This "capillary rise" can take place only when the moisture-films surrounding the soil grains are continuous from the upper to the lower layers of the soil. The process of mulching, by destroying this continuity, prevents or retards the rise and loss of the soil moisture. In sands the capillary films are less numerous, less closely interwoven, and more easily broken, so that when evaporation is at all rapid the surface layer is dried out faster than new moisture can be supplied by capillary rise, and in consequence the connection with the lower moist layers is broken and the rise and loss of water is prevented. Thus, although evaporation from the surface may be very rapid on account of the loose and open texture, the total evaporation from sands is usually less than from more normal soils. The low capillary capacity of sands causes on them the same results which are produced on the soils of arid regions by the intensity of evaporation. The dry surface layer acts as a natural mulch and protects the layers below.[d] Overdrainage and not evaporation, therefore, is responsible for the character of xerophytic dune flora, though the dryness of the surface layer does prevent the growth of shallow-rooted plants, and also the germination of most seeds which find lodgment thereon. The plants

[a] Massart—Bull. Soc. roy. bot. Belg. **32**: 7–43 (1893); Cowles—Bot. gaz. **27**: 95–117, especially p. 109 (1899); Adamović—Bot. Jahrb. **33**: 563–570 (1904); Olsson-Seffer—Bot. gaz. **47**: 85–126 (1909), New phytologist **8**: 37–49 (1909). On dune flora in general see Wesseley—Flugsand, pp. 93–125, 329–332, 339–343 (1873); Warming—Vidensk. medd. Naturh. fören. Copenhagen **43**: 153–202 (1891); Erikson—Bihang K. Svenska vet.-akad. handl. **22**, III, no. 3 (1896); Vuyck—De plantengroei der duinen, 1898; Massart—Rec. Inst. bot. Léo Errera **7**: 167–584 (1907); and the words cited in the bibliography under Alpers, Andresen-Rabenholz, C. Bailey, Baruch, Benzon, von Borbás, Børgesen and Paulsen, Brackebusch, Britton, Bruyne, Buchenau, Buffault, Cockayne, Coulter, Cowles, Davy, Ebner, Focke, Graebner, Hansen, Hanusz, Häpke, Harshberger, C. A. Hart and Gleason, E. J. Hill, Humphrey, Ispolatov, Jännicke, Kalmuss, Kearney, Kerner, Klinge, Klinggraeff, Knuth, Koch, Liebe, McDonald, Mankowski, Massart, Mertens, G. F. W. Meyer, Müller, Nilsson, Nöldeke, Pančič, Pound and Clements (pp. 246–262), Ratzeburg, Razeburg, Reclus, Riefkohl, Royer, Sajó, Schaefer, Senden et al., Sprenger, Suomalainen, Swellengrabel, Tansley, Thesleff, Viborg, and Wery. Bibliographies are given by Cowles—Bot. gaz. **27**: 388–391 (1899); and Massart—Rec. Inst. bot. Léo Errera **7**: 519–537 (1907).

[b] Bull. **38**, Bur. of Soils, U. S. Dept. Agr., pp. 9–18 (1907).

[c] This is, of course, in a soil without plant cover. Transpiration is excluded.

[d] See Bull. **38**, Bur. of Soils, U. S. Dept. Agr., pp. 18–24 (1907).

which are best adapted to dune life[a] are fairly deep-rooted, and often propagate themselves by means of roots extending beneath the surface.[b]

The constant presence of moisture a few inches below the surface of all dunes, desert or humid, has been frequently observed.[c] Where the water table is close to the surface this internal moisture may be due to capillary rise, but the height to which water will rise in uniform sand is not great, and in the majority of cases the dune moisture must be rain or dew which has been absorbed at the surface and retained.[d] This is especially the case in the desert and it is this property of sand which makes possible the little agriculture which the desert will support. The occasional rainfall sinks at once into the sand, and, protected from evaporation, flows easily and quickly to the lower layers, becoming available to plants growing in the oases situated in depressions of the surface.[e] The frequent existence of running, or rather moving, water within easy reach of the surface in

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[a] See the papers cited on p. 71, especially those of Cowles.

[b] As, e. g., the well-known sand-binder, the beach grass (*Ammophila arenaria*). A photograph showing the means of propagation of this plant is given by Westgate—Bull. **65**, Bur. of Plant Ind., U. S. Dept. Agr., Plate II (1904).

[c] Forchhammer—Neues Jahrb. Min. **1841**: 5; Andresen—Om Klitformationen, pp. 106–110 (1861); Lenz—Timbouctou, vol. **2**, pp. 54, 61 (1886); Laurent—Mémoire sur le Sahara, pp. 11–13 (1859); J. C. Brown—Pine plantations on the sand wastes of France, pp. 86–87 (1878); Wilkinson—Peterm. Mitth. **38**: 72 (1892); Gerhardt—Handbuch des Dünenbaues, p. 103 (1900); Cornish—Geog. jour. **15**: 12 (1900); Harshberger—Proc. Acad. Nat. Sci. Phila. **1900**: 626; Richthofen—Führer für Forschungsreisende, p. 117 (1901); Benbow—Agr. gaz. N. S. Wales **12**: 1252 (1901); Fippin and Rice—Field operations, Bur. of Soils **1901**: 99; Braine—Proc. Inst. civ. eng. **150**: 389 (1902); Macbride—Science (n. s.) **21**: 93 (1905); H. P. Baker—Proc. Iowa acad. sci. **13**: 209 (1906); MacDougal—Botanical features of North American deserts, p. 90 (1908), etc. The presence of moisture in dune sands is well illustrated at many points in the Colorado Desert (and probably elsewhere) by the greenness of the bushes (mainly *Covillea tridentata*) growing thereon, while bushes growing on less sandy soils are yellow and faded.

[d] See Andresen's experiments (Om Klitformationen, pp. 106–110 [1861]); and cf. Rolland—Compt. rend. Soc. géog. Paris **1890**: 158–165; Rohlfs—Zs. Ges. Erdk. Berlin **28**: 296–305 (1893); and Braine—Proc. Inst. civ. eng. **150**: 389 (1902). In the heart of the Takla-makan desert Hedin dug a well. The sand was moist 3 feet below the surface and continued so to a depth of 10½ feet, when it became perfectly dry (Through Asia, vol. **1**, p. 533 [1899]; Peterm. Mitth. Ergänzungsh. **131**: 244 [1900]).

It is of course possible, as suggested by Olsson-Seffer (New phytologist **8**: 39–44 [1909]), that some dune moisture may be due to internal dew formation, the water coming from lower layers moistened by the ground waters. Buckingham's experiments above cited indicate, however, that the amount of water thus transferred can not be great.

[e] See Kearney—Bur. plant ind., U. S. Dept. Agr. Bull. **86**, (1905); Laurent—Mémoire sur le Sahara, p. 14 (1859). On the absorption and storage of water by the dune sands of the Arkansas Valley, see Darton—U. S. Geol. surv. Prof. pap. **52**: 84 (1906), and Slichter—ibid. Water sup. pap. **153**: 54 (1906).

depressions and along dry water courses is a commonplace of desert geology. The native wells of the arid southwest, the water holes of the Kalihari, the "soakages" of central Australia are all evidences that in these deserts at least the aridity is of the surface only. Even in the deserts of the most complete aridity, as, for instance, the Taklamakan, ground water can be gotten by digging in wide areas contiguous to the borders and to internal depressions or stream valleys. Of course, this underground water may sometimes be derived from lower water-bearing strata whose supply originates outside the desert basin. Such are probably the artesian strata of the Sahara, Central Australia, parts of Arizona, etc.; and Lyons[a] believes that all the oases of the Libyan Desert are situated on the summits of anticlines and fed by waters rising from below. In most cases, however, external supply is impossible and the desert ground water must be from rainfall in the desert basin and on its watershed, which rainfall is absorbed and conserved in the deep sandy soils. Travelers in the desert speak often of the "intense evaporation" which leaves the soil dry a few minutes after a heavy shower. Of course, evaporation is intense, but the disappearance of the rain water from the surface soil is due as much to absorption as to evaporation.

Though dune areas are usually barren, the sands are not infertile in the sense that they lack the mineral elements of plant food.[b] Except for an occasional occurrence of nearly pure quartz, drifting sand contains the ordinary soil minerals in sufficient quantities to sustain the growth of plants, and wherever dunes or other sandy tracts have been reclaimed they have proven perfectly capable of supporting an agriculturally valuable vegetation. The great potential fertility of desert soils is well known and all travelers and residents therein have noticed the rapidity with which the desert will spring to life after a rain.[c] The barrenness of dune areas is due to lack of water and to instability of surface rather than to any deficiency of mineral plant nutrients; but like all loose, porous soils, dune sands lack humus on account of the activity of the processes of oxidation. The vegetable matter is "burnt out," and both for this reason and on account of the physical disadvantages of sandy structure, dune sand seldom forms soil of

[a] Quart. jour. Geol. soc. **50**: 531 (1894). On the theory of Courbis that the great dunes of the Sahara owe their position and fixity to the escape of water underneath their site, see Courbis—Compt. rend. Soc. géog. Paris **1890**: 114–119, 256–261; Rolland—ibid., pp. 158–165; Garnier—ibid., pp. 305–306; Bernard—ibid., pp. 320–323; and Blanc—Ibid., pp. 363–372. Cf. the observations of Horusitzky on the underground source of the moisture of the dunes of northwestern Hungary (Földtani Közlöny **34**: 373–375 [1904]).

[b] Wesseley—Flugsand, pp. 42–47, especially p. 47 (1873).

[c] See, e. g., Wellsted—Travels in Arabia, vol. **1**, p. 182 (1838); Przhevalskĭĭ—Reisen in der Mongolie (German ed.), p. 491 (1881); Schirmer—Le Sahara, pp. 22–23 (1893); W. J. H. King—Masked Tawareks, p. 226 (1903); etc.

unusually high value. Suitable plants will, however, grow very well on it, and many dune areas now waste could be agriculturally utilized if properly handled.

THE CONTROL OF DRIFTING SANDS.

The first step in the control and utilization of dune areas is the stopping of sand movement and the establishment of a stable and permanent surface. Such fixation is sometimes profitable because of the value of the lands thus made available for agriculture, but more often the work of control is rendered advisable on account of the encroachment of the moving sands on more valuable land or on works of man. In many parts of the world coastal dunes have caused great damage to agricultural lands and in some cases to harbors, seashore villages, etc.[a] Interior moving dunes are no less troublesome and have frequently to be fought by the railways which pass through them as well as by the owners of adjacent lands and buildings. In the United States drifting sands have proven a menace on Cape Cod and Cape Hatteras, at the southern end of Lake Michigan, along the Columbia River in Oregon and Washington, at San Francisco, and in many small areas elsewhere.[b] The interior areas of drifting sand in North America are fortunately not extensive.

According to the methods usually employed, the fixation of a dune area begins with the planting of some grass or similar plant which

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[a] See Élie de Beaumont—Leçons de géologie pratique, vol. **1**, pp. 199–213 (1847); Andresen—Om Klitformationen, pp. 223–236 (1861); Reclus—Bull. Soc. géog. France (5) **9**: 210–212 (1865); Wesseley—Flugsand, pp. 221–222 et al. (1873); Topley—Pop. sci. rev. **14**: 138 (1875); Czerny—Peterm. Mitth. Ergänzungsh. **48**: 28 (1876); Marsh—The earth as modified by human action, pp. 565–567 (1885); Merrill—Eng. mag. **2**: 602 (1892); Gifford—Ibid., **14**: 605 (1898); Le Mang—Deut. geog. Blätt. **22**: 240–245 (1899); Gerhardt—Handbuch deut. Dünenbaues, 150–170 (1900); Davy—U. S. Dept. Agr., Bur. plant ind. Bull. **12**: 56–57 (1902); Millar—Chambers's jour. (6) **8**: 236–237 (1905); Cobb—Nat. geog. mag. **17**: 313–314 (1906); J. H. Pratt—Jour. Elisha Mitchell sci. soc. **24**: 125–138 (1908); Gray—Buried City of Kenfig, pp. 13–35, (1909); and the works cited on pp. 54–56 above and note *c* below.

[b] See the works cited on pp. 54–56 above.

[c] Any extended discussion or review of the literature of dune control is outside the scope of this bulletin. The general methods employed (with special reference to European conditions) are fully described by Gerhardt—Handbuch des deutschen Dünenbaues (1900). See also Wesseley—Der europäischen Flugsand und seine Kultur, (1873); Fisher—Forest protection, pp. 524–538 (1895); and A. S. Hitchcock—Bull. **57**, Bur. plant ind. U. S. Dept. of Agr. (1904). The procedure employed in Cape Colony, South Africa, is described by Braine (Proc. Inst. civ. eng. **150**: 376–397 [1902]); that in use in Australia, by Benbow (Agr. gaz. N. S. Wales **12**: 1249–1254 [1901]), and Maiden (Jour. Proc. Roy. soc. N. S. Wales **37**: 82–106 [1903]); and that of the Chilean coast by Albert (Actas Soc. cient. Chile **10**: 135–317 [1900], **11**: 129–151 [1901]).

The important North American literature, so far as known to the author, is Scribner—Yearbook U. S. Dept. Agr. **1894**: 421–436, **1898**: 405–420; Gifford—Eng. mag. **14**: 603–614 (1898); Saunders—Rept. Canada expt. farms **1901**: 62–77, **1902**: 55–58; Davy—U. S. Dept. Agr. Bur. plant ind. Bull. **12**: 56–62 (1902); Westgate—U. S. Dept. Agr. Bur. plant ind. Bull. **65** (1904); J. Fletcher—Canad. forestry jour. **1**:

will bind the surface and protect it from attack by the wind. The particular plant which is most useful in any individual case depends upon the general ecological environment as well as upon the efficiency of the plant as a sand binder,[a] and many different plants have been successfully used in different parts of the world. Of these the marram or beach-grass (*Ammophila arenaria*)[b] has been found particularly useful in temperate climates, and especially so upon coastal dunes.[c]

182–184 (1905); H. P. Baker—Proc. Iowa acad. sci. **13**: 209–214 (1906); Bond in J. H. Pratt—Jour. Elisha Mitchell sci. soc. **24**: 125–138 (1908); Zavitz—Rept. on reforest. of waste lands S. Ont. (1909); and the reports of the Massachusetts commissioners and of the United States engineers, cited on p. 54–55 above.

Other literature on dune control is given in the bibliography under A. R., About, Agŕeev, Alker, Bagneris, F. Bailey, Bale, Bang, Bátky, Baude, Bayberger, Bechtel, Begg von Albansberg, Bernatskĭĭ, Bert, Bĭelov, Biörn, Blijdenstein, Boitel, von Borbás, Bortier, J. C. Brown, Buffault, Burgsdorf, Bykovskĭĭ, Chambrelent, Chumakov, W. R. Clarke, Clavé, Cockayne, Cotton, Crawford, Curzon (pp. 55–58), Davydov, Dehillotte-Ramordin, Delamarre, Deminskĭĭ, Elisŕeev, Engler, Fabre, Faye, Feilberg, Gee, Gerhardt, Girardin, Gleditsch, Grempe, Hartig, Hedin (Khorasan och Turkestan, vol. 1, p. 239), Hesselman, Heywood, Hofschneider, Hubeny, Hubert, Ivanovskĭĭ, Izvŕestiă M-stva zemled. gosud. imushchestv., Jentzsch, Kargl, Karsten, Keffer, Kerner, Kirk, Klinsmann, Knüpffer, Kolesov, Konoval, Kostŕaev, Kozakovskĭĭ, Krasilshchikov, Kummer, Lakin, Laveleye, Lefort, Le Mang, Lidbeck, Lindner, Lomonosof, Lozovskĭĭ, Luiggi, M., M. P., McNaughton, Makarov, Malakhov, Mankowski, Märker, Marshall, Mattusch, Meguscher, Molnár, Montin, Müller, Negelein, Nikitin, Nilsson, Paletskĭĭ, von Pannewitz, Pfeil, Poisson, Ploetz, Pravitelstven. Vŕestnik, Privat-Deschanel, Raspopinskĭĭ, Rauner, Reclus, Reinke, Riston, Sajó, Salomon, Samanos, Schelten, Schreber, Schumacher, Sharin, Siemssen, Sobolev, Spasskĭĭ, Sprenger, Stewart, Titius, Tolle, Tourgee, Travers, Tsĭolkovskĭĭ, U. S. Forest service, Vasselot de Régné, Viborg, Vŕernŕeev, Volkov, Weidenkeller, Whitcombe, Willey, and Witsch. Wesseley (Flugsand, pp. 256–264) gives a list of Hungarian and German articles. Most of the early Hungarian literature there cited is not included here. Much of the extensive Russian literature is also omitted but will be found, for the most part, in the columns of the Lŕesnoĭ zhurnal.

[a] The general principles underlying the action of vegetation as a protection against wind erosion have been discussed on pp. 28–29.

[b] Also known as *Ammophila arundinacea*, *Psamma arenaria*, and *Arundo arenaria*.

[c] On its use see A. S. Hitchcock—Bull. **57**, Bur. plant ind. U. S. Dept. Agr. (1904); Westgate—Bull. **65** of the same bureau, 1904; etc. On its use in the interior of Australia see Maiden—Agr. gaz. N. S. Wales **6**: 7–12 (1895). On sand-binding plants in general see Viborg—Beschreibung der Sandgewächse, etc., 1789; Cleghorn—Hooker's jour. bot. **8**: 52–54 (1856); Borggreve—Verh. naturh. Ver. preuss. Rheinl. Westf. **32**, Cor.-bl.: 69–72 (1875); Barrande—Bull. Soc. géog. Paris (6) **17**: 376 (1879); Crawford—Trans. Proc. Bot. soc. Edinb. **14**: 351–355 (1883); von Borbás—Bot. Centbl. **19**: 92–94 (1884); Buchenau—Abh. naturw. Ver. Bremen **10**: 397–412 (1889); Clarke, in Watts—Dict. econ. prods. India **6**: 455–457 (1893); Scribner—Yearbook U. S. Dept. Agr. **1894**: 421–436, **1898**: 405–420, Bull. Div. of Agrostology, **14**: 78 (1898); Gerhardt—Zs. Bauwesen **47**: 453–466 (1897); Davy—U. S. Dept. Agr. Bur. plant ind. Bull. **12**: 57–62 (1902); Sajó—Prometheus **13**: 769–773 (1902); Roberts—Kansas Agr. expt. stat. Bull. **121**: 139–141 (1904); Bessey—Vegetationsbilder **3**, Heft 2: text for Tafeln 7 and 8 (1905); Kirk—Rept. N. Z. Dept. Agr. **15**: 180–185 (1907); Massart—Rec. Inst. bot. Léo Errera **7**: 268–272 (1907); Gill—Jour. Dept. Agr. South Aust. **11**: 1030 (1908); and the general works on dune control above cited and on dune flora cited on p. 71.

After the preliminary fixation has been accomplished dune lands are in the vast majority of cases best put into forest, not alone because trees are excellent protectors against wind action, but because they can be made to yield a considerable financial return without any danger of again starting the sand drift. Thus the pine plantations on the great "landes" of Gascony not only fix the dunes and protect the country from their encroachment, but furnish as well a considerable revenue in the form of turpentine, rosin, and wood.[a] In general, however, trees can not be made to grow on naked dunes, and hence the necessity for a preliminary fixation with grasses or other hardy plants.

The fixation of a dune not only prevents damage to plants by the actual moving of the surface, but it betters the quality of the soil itself by causing the retention of the finer products of weathering and decay which are winnowed out of moving sands and blown clear away A stationary dune always contains much dust,[b] which greatly betters the soil both physically and chemically and enables it to support a more varied and valuable flora.

The fixation of dunes, and especially of coastal dunes, often takes place by natural processes. The force of the on-shore breezes decreases rapidly with distance from the beach,[c] and the rate of inland movement of the dunes soon decreases sufficiently so that the hardier of the plants can take possession and begin the work of fixation. With increasing permanence of surface and progressive decay of the sand, plants of less hardihood can and do take hold until finally natural forests arise and the fixation becomes complete.[d] On most

[a] The reclamation of these great sand wastes was begun by Brémontier in 1787, and forms probably the most extensive and best known example of dune utilization. For further details see Brémontier—Jour. l'École polyt. Paris **2**: 61–70 (1797) and Ann. ponts chauss. **5**: 145–191 (1833); Gillet-Laumont, Tessier and Chassiron—Rapport sur les Mémoires de M. Brémontier (1806); also reprinted in the Ann. ponts chauss. (loc. cit. pp. 192–224); J. C. Brown—Pine-plantations on the sand wastes of France (1878); Poore—Essays on rural hygiene, pp. 353–369 (1894); Grandjean—Bull. Soc. géog. comm. Bordeaux (2) **19**: 238–246 (1896); Le Mang—Deut. geog. Blätt. **22**: 235–255 (1899); Bert—Les Dunes de Gascogne (1900); Durègne—Actes Soc. linn. Bordeaux. **57**: 1–10 (1902); Engler—Naturw. Wochens. **17**: 277–282, 292–295 (1902), etc.

[b] Shaler—Bull. Geol. soc. Amer. **5**: 211–212 (1894). Cf. Atterberg—Chemztg. **29**: 1074 (1905). This conclusion is confirmed by a number of mechanical analyses of sand from fixed and moving dunes made in the Bureau of Soils on samples collected by the writer.

[c] On account of the higher resistance of land surface to the air currents; see Thos. Stevenson—Jour. Scott. meteor. soc. **5**: 103–108, 348–351 (1880); Nature **25**: 607 (1882), **27**: 432–433 (1883); Sokolov—Die Dünen, pp. 9–12 (1894).

[d] On natural fixation see Travers—Trans. New Zealand inst. **14**: 91 (1882); Brackebusch—Peterm. Mitt. **39**: 157 (1893); Cowles—Bot. gaz. **27**: 300 et seq. (1899); Adamović—Bot. Jahrb. **33**: 560–561 (1904); Massart—Aspects de la végétation en Belgique, vol. **1**, plates 10–13 (1908); Stevens—U. S. geol. surv. Water-supp. pap. **230**: 220 (1909); Humphrey—Plant world **12**: 81–82 (1909); etc.

coasts this natural fixation would become operative within a comparatively short distance from the shore were nature's processes allowed to remain undisturbed. In fact, before human interference began all coasts where sand is driven landward were probably protected by a belt of these naturally fixed and forested dunes. The present trouble with coastal dunes is due almost entirely to the unrestricted exploitation of the timber, which left the sands exposed and ready to recommence their drifting.[a] Nor does the trouble stop here, for improvident grazing and cutting of new growth prevents the natural fixation which would otherwise take place. It is essential for the safety of much coastal land that the shore-line growth be carefully and firmly protected against exploitation. Protection is cheaper than reclamation.

DUST STORMS AND DUST FALLS.

All strong winds pick up much dust from the soil surface, and if loose material be plentiful the wind storm will become a dust storm and the air so thickly filled with dust that it will be difficult to see or to breathe. Such storms are the sudden paroxysms of atmospheric transport, quite analogous to the floods of streams and rivers. They are striking, unusual, and abnormally intense manifestations of that eolian translocation which is constantly going on more quietly and more slowly and probably in much greater total amount.

Dust storms are of occasional occurrence everywhere, but they find their especial province on the great steppes or high semiarid plains of the continental interiors, where the soil is comparatively thinly covered by vegetation and the winds find nothing to break their force. On the great plains of this character in eastern Europe and the contiguous portions of Asia dust storms are of almost daily occurrence during the drier seasons of the year. In the deserts also all strong winds are dust laden and a tremendous quantity of material is moved, both as fine dust and as drifting sand. The quantity of the latter is often so great that small objects are rapidly buried

[a] For instance, the drifting sands of Cape Hatteras were probably started by timber cutting just after the civil war (Cobb—Nat. geog. mag. **17**: 313, note [1906]). The cutting of the forests on the North German coast because Frederick I needed money has since cost the German Government (in reclamation work) many times the amount obtained for the timber (Müller—Das Buch der Pflanzenwelt, vol. **1**, p. 16 [1857]). For other notices of the starting of sand drift by improvident exploitation, see Reclus—Bull. soc. géog. France (5) **9**: 216–218 (1865); Travers—Trans. New Zealand inst. **14**: 90–93 (1882); Marsh—The earth as modified by human action, ed. of 1885, p. 556; Heywood—Report on drift sands, 1893; Thesleff—Medd. Geog. fören. Finland **2**: 36–77 (1894); Lorenzen—Die Natur **48**: 424–426 (1899); Fabre—Compt. rend. Cong. géol. intern. **8**: 790–791 (1900); Bertololy—Kraüselungsmarken und Dünen, p. 163 (1900); Adamović—Bot. Jahrb. **33**: 561 (1904); Pratt—Jour. Elisha Mitchell sci. soc. **24**: 125–138 (1908); and the various works on dune control cited on pp. 74–75.

and tracks of men or animals obliterated in a few moments.[a] The tales[b] of the burial of caravans and armies by sand storms are doubtless fabulous,[c] but these storms are really very severe and it is difficult, though perhaps not actually dangerous, to face them.[d]

But the desert storms carry much fine dust in addition to the drifting sand, and this dust is of even greater importance geologically and to the soil, for fine materials are not confined to the desert as is the sand, but can be, and are, carried across its borders into the more humid areas beyond. This subject has already been briefly discussed and it has been pointed out that the removal of weathered material from desert areas is entirely effected in this way, both by the action of storms and by the constant carrying of small quantities of dust by ordinary winds.

There are thus two general types of dust storms. The one blows dust from place to place over the steppes or other regions of poorly protected soil, attacking the surface as it goes; the other collects dust from the desert and carries it outward over and into regions which it can not attack and where no new load can be obtained. The distinction between these two types is convenient rather than necessary; they are marked by no essential differences in nature; they are separated by no sharp line. It is, of course, apparent that a dust storm may originate in a steppe area, collect dust there and carry it outward as does a storm of the desert class; while, on the other hand, so long as a dust storm is within the confines of the desert, it parallels exactly the behavior of a storm of the steppes. The utility of the distinction lies in the fact that the storms of the steppes carry dust into other areas far less often than do those of the desert. Furthermore, the behavior of the desert storms within the desert is of little interest, Only their external effects are of importance.

It has already been pointed out on page 48 that in storms of the steppe character, and in fact in all storms blowing over an attackable surface, the materials of the load do not remain the same from place to place, but that there is a constant interchange between the air and

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[a] For an instance see Wellsted—Travels in Arabia, vol. 1, p. 88 (1838).

[b] E. g., the army of Cambyses (Herodotus, book III, chap. 26). See also the legends of the burial of cities in the Takla-makan desert, quoted from early travelers by Stein—Sand buried ruins of Khotan, pp. 430, 439 (1903).

[c] See Palgrave—Narrative of journey through Arabia, vol. 1, p. 17 (1865); Rolland—Rev. sci. (3) 1: 612 (1881).

[d] For first-hand descriptions of desert sand storms see Tristram—The great Sahara, p. 331 (1860); Duveyrier—Les Touareg du Nord, p. 40 (1864); Benjamin—Bull. Amer. geog. soc. 18: 33 (1886); Bolton—Trans. New York acad. sci. 9: 115–116 (1890); Schaubert—Globus 71: 93 (1897); Hedin—Through Asia, vol. 1, p. 516, 542 (1899); W. J. H. King—Masked Tawareks, p. 133–134 (1903); Stein—Sand buried ruins of Khotan, pp. 428–429 (1903); J. W. Gregory—Dead heart of Australia, p. 98 (1906); etc. Albert describes a similar storm in the dune area on the Chilean coast (Actas Soc. cien. Chile 10: 171 [1900]).

the soil. The result of this interchange is that in passing over such country dust storms may neither raise nor lower the mean level of the surface, for the material removed is in general replaced by other material deposited. It does not follow that dust storms have no important action, for it is precisely this interchanging translocation which most highly promotes the mixing of soils—perhaps the most important (agriculturally at least) of the varied geologic activities of the wind.

In the western part of the United States dust storms of both types are of frequent occurrence. The desert storms arise in the arid basins of New Mexico, Arizona, Utah, and southern California, and carry dust sometimes westward toward the Pacific slope and sometimes eastward into the plains region of Oklahoma and Texas. The storms of the steppe type occur on the Great Plains extending from northern Texas and northeastern New Mexico northward through Oklahoma, eastern Colorado, western Kansas, Minnesota, and the Dakotas well toward the Arctic Circle. Udden [a] has collected accounts of thirty-nine storms during 1894 and 1895, one or more of which occurred in each of fourteen States. He estimates that on the average for the country between the Rocky Mountains and the Mississippi River the minimum yearly number of such occurrences is two and the maximum four, while for the Great Basin and the Western Slope the figures are five and twenty, respectively. Many instances occurring before and after the period examined by Udden are recorded in the columns of the Monthly Weather Review.[b] The conditions in Australia are quite similar to those in the Western United States, and dust storms are of frequent occurrence.[c] China

[a] Pop. sci. mon. **49**: 655–664 (1896).

[b] E. g., **23**: 13, 15–19, 52, 130, 381 (1895); **29**: 465 (1901); **30**: 29 (1902); **33**: 350 (1905); **35**: 583 (1907); **36**: 103 (1908). See also Amer. geol. **3**: 397–399 (1889); Tarr—Amer. nat. **24**: 455–459 (1890); Somers—Science **21**: 303 (1893); Hershey—Amer. geol. **23**: 380–382 (1899); Russell—U. S. Geol. surv. Bull. **199**: 18, 21 (1902); Reagan—Science (n. s.) **28**: 653 (1908); and Mendenhall—U. S. Geol. surv. Water sup. pap. **225**: 27 (1909). Dust storms, mostly of local origin, in the Central and Eastern States are described in the Monthly weather review **17**: 89 (1889); **23**: 130 (1895); **30**: 269 (1902); **31**: 536 (1903); **37**: 156 (1909); and by Cutting—Archives of sci. **1**: 81–85 (1870); Somers—loc. cit.; J. W. Moore—Science (n. s.) **15**: 714 (1902); McLouth—Rept. Mich. acad. sci. **4**: 168–173 (1902); Verrill—Science (n. s.) **15**: 872 (1902); Baskerville and Weller—ibid. p. 1034; Lindsey—ibid. **19**: 893 (1904). Keyes has published observations on the dust storms of the Missouri Valley (Amer. jour. sci. (4) **6**: 299–304 [1898]).

[c] Sturt—Central Australia, vol. **2**, p. 97 (1849); Tenison-Woods—Jour. Proc. Roy. soc. N. S. Wales **16**: 78–79 (1882); Smyth—Nature **30**: 170 (1884); H. C. Russell—Quart. jour. Roy. met. soc. **13**: 311–312 (1887); Brittlebank, Stickland, and Shephard—Vict. nat. **13**: 125 (1897); Steel—Rept. Austr. assoc. adv. sci. **7**: 334–335 (1898); Phipson—Chem. news **83**: 159–160, 253 (1901); Liversidge—Jour. Proc. Roy. soc. N. S. Wales **36**: 255–272 (1902); Mullen—ibid. **37**: 144 (1903); Chapman and Grayson—Vict. nat. **20**: 17–32 (1903); Dixon—Nature **67**: 203 (1903); Dove—ibid.; P. Marshall—ibid. **68**: 223 (1903); Noble—Mon. weath. rev. **32**: 364–365 (1904); Krebs—Beitr. Geophys. **8**: 34 (1906).

is subject to storms of the desert type, arising in the central Asian deserts,[a] and similar phenomena are encountered in other parts of the earth.[b] Even in the Arctic regions dust storms are not unknown.[c] The well-known falls of sirocco dust in southern Europe will be later discussed in detail.

Showers of fine dust sometimes occur unaccompanied by any strong wind. Such an occurrence must be regarded simply as the final stage of a dust storm which has lost its velocity and is depositing its load. Indeed, if the dust has been traveling in the higher strata of the atmosphere it may fall into and be deposited by winds very different in direction from that by which its transport has been effected. Similarly the dust may be carried down by rain or snow, causing the muddy rains, black snows, etc., frequently mentioned in the daily press.

MATERIAL MOVED BY DUST STORMS.

The amount of material carried by dust storms is naturally difficult to determine, but is certainly quite considerable. From various

[a] W. H. Johnson—Jour. Roy. geog. soc. **37**: 1–47 (1867); Przhevalskiĭ—Mongolia **2**: 219 (1876); Pumpelly—Amer. jour. sci. (3) **17**: 139 (1879); Guppy—Nature **24**: 126 (1881); Harrington—Amer. meteor. jour. **3**: 79–82 (1886); Lehzen—Globus **56**: 361 (1889); Minssen—Annalen Hydrog. **30**: 552 (1902); Takagi—Kisho Sh. **25**: 219–232 (1906).

[b] In Egypt: Barron and Hume—Topography Eastern desert of Egypt, pp. 93–97, 287 (1902). In Arabia: Wellsted—Travels in Arabia, vol. **2**, p. 150 (1838); von Benko—Reise Schiffes "*Frundsberg*," p. 61 (1888); Walther—Einleitung in der Geologie als historische Wissenschaft, p. 578 (1894); Oesselmann—Annalen Hydrog. **30**: 552 (1902); Annales Hydrog. (2) **24**: 159 (1902); Prager—Annalen Hydrog. **31**: 22–23 (1903). In India and Central Asia: Baddeley—Whirlwinds and dust storms in India (1860) and articles cited in the bibliography; Durand—Compt. rend. Assoc. Franç. avan. sci. **7**: 474–477 (1878); Cook—Quart. jour. Roy. meteor. soc. **9**: 137–147 (1883); Obruchev—Geog. Zs. **1**: 261 (1895); Hedin—Through Asia, vol. **1**, p. 446, 458–463, 468, 498 (1899), Scientific results, vol. **1**, p. 247–248, 289–293 (1904); Abbe—Mon. weath. rev. **29**: 175 (1901); Morozsevich—Bull. Comm. géol. St. Petersburg **22**: 48–49 (1903); Huntington—Pulse of Asia, p. 97, 157, 299 (1907). In Persia: Tietze—Jahrb. geol Reichsanst. **27**: 347–348 (1877); Benjamin—Bull. Amer. geog. soc. **18**: 33 (1886); Schaubert—Globus **71**: 93–94 (1897). On the steppes of southeastern Europe and adjacent portions of Asia: Middendorff—Sibirische Reise, vol. **4**, p. 385 (1875); Nehring—Tundren und Steppen, p. 127 (1890); Klossovskiĭ—Ciel et terre **15**: 559–566 (1895); Ileintz—Poln. entsik. russ. selsk. khoz. **8**: 50–51 (1903). In South America: Darwin—Journal of researches, p. 133, ed. of 1901; Christison—Jour. Scott. meteor. soc. **5**: 335–347 (1880); Annalen Hydrog. **17**: 350–351 (1889); Bodenbender—Peterm. Mitth. **39**: 237 (1893); Machon—Bull. Soc. Vaud. sci. nat. (4) **39**: xxxiii (1903). In Europe: Buchholz—Wetter **10**: 144 (1893); Yates—Nature **55**: 508 (1897); Denham—ibid. **65**: 317 (1902); Fry—ibid. p. 317; C. Reid—ibid. p. 414; Mill—Quart. jour. Roy. meteor. soc. **28**: 229–252 (1902); Marriott—Nature **67**: 391 (1903); Boeddicker—Symons's meteor. mag. **43**: 2–4 (1908). In Iceland: Thoroddsen—Peterm. Mitt. **31**: 285, 287, 290, 291, 293, 330, 332 (1885); Meunier—Compt. rend. **136**: 1713–1714 (1903).

[c] See Davison—Quart. jour. Geol. soc. **50**: 479 (1894) and authorities there cited.

indirect data Udden [a] has made a series of estimates of the amount of solid material suspended in the air during a dust storm, and has obtained values ranging from 160 to 126,000 tons per cubic mile of air. The wide variation is due to the varied, indirect, and inaccurate character of the data upon which the estimates are based. Taking very conservative values derived from these estimates, and using rather more accurate data for the number, velocity, and duration of dust storms in the Western States, he concludes that on the average about 850,000,000 tons of dust is carried 1,440 miles each year, thus doing in this region alone about 1,225,000,000,000 "mile tons" of transport.

The amount of material suspended in the air during a dust storm is not, however, so good a measure of the translocation thus effected as are measurements of the material actually deposited on the surface or removed therefrom. The deposits made by the dust storm of January 11–12, 1895, in Indiana, were measured at several points and found to vary from 1.50 grams per square meter (4 tons per square mile) to 3.79 grams per square meter (10.5 tons per square mile).[b] The thickness of the deposit was measured at Rockville, Ind., and found to be about 0.02 inch.[c] At this point the quantity of dust was 1.5 grams per square meter, which is the minimum observed, and it is therefore probable that at other points the layer of deposited dust had a thickness as great as, if not greater than, the value given. It is difficult to generalize from so meager data, but in the light of the known frequent occurrence of dust storms over the States west of the Mississippi, it seems not extreme to estimate the mean annual deposit[d] over this area as not less than 0.01 inch.[e] In some places the rate of deposit is much greater,[f] but even at the figure given soil would accumulate at the rate of 1 inch per century, which is quite rapid in comparison with most geologic processes.

Estimates of the deposit by two Australian storms are given by Chapman and Grayson[g] as 17.5 grams per square meter (50 tons per

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[a] Pop. sci. mon. **49**: 658–663 (1896).

[b] Mon. weath. rev. **23**: 17–18 (1895).

[c] Campbell—Mon. weath. rev. **23**: 18 (1895).

[d] Desert areas must, of course, be excluded since it is largely there that the dust originates and the tendency is toward a lowering rather than a raising of the surface. There are, too, occasional places other than deserts where the soil is removed rather than deposited. It might be more correct to say "mean annual transfer" instead of "mean annual deposit." See in this connection p. 48 above.

[e] Keyes estimates the annual deposit of the dust storms along the Missouri River as 0.01 inch (Amer. jour. sci. (4) **6**: 302 [1898]), and Shimek estimates the rate of accumulation of Mississippi Valley eolian loess as 1 mm. (0.04 inch) a year (Bull. Lab. nat. hist. Univ. Iowa **5**: 320 [1904]).

[f] For instance, the deep drifts of soil deposited by the storm of April 15, 1895, in western Kansas and described in the Mon. weath. rev. **23**: 130 (1895).

[g] Vict. nat. **20**: 21–22 (1903).

square mile) and 12.5 grams per square meter (35.5 tons per square mile), respectively. So much soil was blown about during the dry seasons of 1827 to 1830 in South America that the boundaries of many estates were obscured and in some cases permanently lost.[a] The quantities of dust carried into Europe by dust storms originating in the Sahara are estimated on pages 97 et seq., below.

Inside the deserts much larger quantities of sand and dust are moved about, but it is impossible to distinguish between the drifting sand of the dunes and the finer material carried by dust storms. As already mentioned, the general tendency is toward a lowering of the desert surface, but there are undoubtedly many cases of local accumulation of dust as well as of drifting sand. Rohlfs[b] describes a storm which covered his party an inch deep with sand; Zittel[c] records the deposit of 26 cm. of sand on his tent in one storm; and Jordan[d] mentions the deposit of 25 inches on a level spot under similar circumstances. According to Noble[e] drifts of sand 12 feet deep were produced in three months in Australia.

It is probable that in all these cases the deposit was largely drift sand, but Hedin[f] records that the winter dust storms of the Tarim basin deposit so much impalpable dust on the vegetation that it causes the sheep that eat it to have strangles, and Huntington,[g] in the same region, found it necessary to brush his writing paper every ten or fifteen minutes to prevent his pen being clogged by deposited dust.

DISTANCES OF TRANSFER.

The theoretical considerations controlling the distance of transport have been discussed on pages 47–49, and it is there pointed out that authentic instances of long transport are rare, because of the usual impossibility of identifying the dust and the consequent necessity for relying upon indirect evidence as to its source. Occasionally evidence is furnished by the simultaneous existence of the same storm over considerable areas, or by the possibility of tracing the path of the storm by observations made along its path. Udden in his examination of western dust storms, already cited,[h] records the areas thus covered by seven storms (all for which data were

[a] Darwin—Journal of researches, p. 133, ed. of 1901.

[b] Peterm. Mitth. Ergänzungsh. **25**: 11 (1868).

[c] Jahresb. geog. Ges. Munich **4–5**: 258 (1875).

[d] Kölnische Zeitung, Apr. 14, 1874, quoted by Walther (Denudation in der Wüste, p. 504), who cites other similar occurrences.

[e] Mon. weath. rev. **32**: 364 (1904).

[f] Through Asia, vol. **2**, p. 798 (1899). On deposit by these storms see also Scientific results, vol. **1**, p. 291–293 (1904). The deposits may, perhaps, aggregate 2 or 3 meters in a century.

[g] Pulse of Asia, p. 157 (1907).

[h] Pop. sci. mon. **49**: 656 (1896).

available) as 80, 120, 140, 216, 270, 300, and 400 miles in the longest observed direction, giving an average of 218 miles. A Chinese dust storm is known to have existed simultaneously from Hankow to Chinkiang, i. e., over 450 miles.[a] It should be mentioned that these are minimum values, since they represent the distances between points where the storms were observed and recorded. The storms may have covered much wider areas.

The dust which fell in Missouri on February 6 and 7, 1895, must have come from western Kansas and Nebraska, as all the intervening country was covered with snow and ice.[b] A similar case is reported from Norway.[c] On April 2, 1892, there fell on a ship 95 miles west by south of Nagasaki a yellow dust which must have come from the interior of China and have been carried by the wind to the place where it was observed,[d] a distance of at least 1,000 miles. The Australian dust storms have several times reached New Zealand,[e] a distance of about 1,500 miles. Even better examples of long distance translocation are the dust storms originating in the Sahara and traveling over southern and central Europe, as discussed on pages 88 et seq. Dust from these storms has been observed in northern Germany[f] and in England,[g] a distance of about 2,000 miles.[h]

DUST WHIRLWINDS.

Among the most striking of arid region phenomena are the dust whirlwinds or columns of whirling dust-filled air, a few inches to several feet in diameter, and from a few feet to hundreds of feet in height. They may be seen nearly every hot day, sometimes running rapidly over the surface; sometimes remaining nearly, if not quite, stationary, but never losing their rapid rotation. They usually last only a few minutes, but occasionally persist much longer. One observed by Pictet lasted for over five hours.[i] They are largest and last longest on the flat, bare plains of the desert, and are usually seen in a calm or when only a light breeze is blowing, although their

[a] Guppy—Nature **24**: 126 (1881).

[b] Mon. weath. rev. **23**: 52 (1895).

[c] See Liversidge—Jour. Proc. Roy. soc. New South Wales **36**: 250 (1902).

[d] Milne—Nature **46**: 128 (1892). A similar storm occurred on March 31–April 1, 1863. See Pumpelly—Amer. jour. sci. (3) **17**: 139 note (1879).

[e] For instance, see Marshall—Nature **68**: 223 (1903); Chapman and Grayson—Vict. nat. **20**: 29 (1903); Noble—Mon. weath. rev. **32**: 364 (1904).

[f] Judd—Nature **63**: 514 (1901); Hellmann and Meinardus—Monograph cited on p. 90 below.

[g] Mill and Lempfert—Quart. jour. Roy. meteor. soc. **30**: 57–91 (1904).

[h] The distance covered by the storm of March 9–11, 1901, is given by Walther as 2,500 miles (4,000 kilometers). Naturw. Wochens. **18**: 604 (1903).

[i] Colladon—Arch. sci. phys. nat. Geneva (3) **2**: 37–39 (1879).

occurrence in windy weather is not unknown.[a] The rotation seems to be indiscriminately clockwise or contra-clockwise, as frequently one as the other.

These whirls have been noticed by many travelers in desert and steppe regions [b] and have been carefully observed by Baddeley [c] in India, and by Pictet [d] in Egypt.[e] They are frequent in China [f] and on the pampas of South America,[g] and occasionally occur during the

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[a] Baddeley—Whirlwinds and dust storms in India, p. 5 (1860). It is possible that the whirls occurring in windy weather are simply convectional eddies, and not formed by the causes producing the typical calm weather whirls. See p. 88 below.

[b] Burnes—Travels into Bokhara, vol. **3**, p. 40 (1834); Stephenson—Bibl. univ. (n. s.) **6**: 155–156 (1836); Örsted—Schumacher Jahrb. **1838**: 228–254; Goebel, Claus, and Bergmann—Reise in die Steppen südlichen Russlands, vol. **1**, p. 202 (1838); Peltier, in Becquerel—Traitè expérimental de électricité et du magnétisme, vol. **6**, p. 184–189 (1840); Martins—Ann. météor. France **1**: 225–244 (1849); Muncke, in Gehler's Physikalisches Wörterbuch, vol. **10**, p. 1635–1723 (1842); W. Reid—Attempt to develop the law of storms, 3d ed., p. 469 (1850); Junghuhn—Java, vol. **2**, p. 572, 584 (1854); Belt—Phil. Mag. (4) **17**: 47–53 (1859); Tristram—The Great Sahara, p. 67 (1860); Schlaefli—Zs. Meteor. **5**: 469–472 (1870); Tietze—Jahrb. geol. Reichsanst. **27**: 347–348 (1877); Durand—Compt. rend. Assoc. franç. avan. sci. **7**: 475 (1878); Hooker and Ball—Marocco and the Great Atlas, p. 122 (1878); H. H. Russell—Quart. jour. Roy. met. soc. **6**: 48 (1880); Cook—ibid., **9**: 141 (1883); Faye—Compt. rend. **97**: 125–127 (1883); Russell—Ann. Rept. U. S. Geol. surv. **3**: 197 (1881–82); Wolkowitz—Annalen Hydrog. **15**: 437 (1887); Brewer—Bull. Amer. geog. soc. **21**: 211 (1889); Abercromby—Quart. Jour. Roy. meteor. soc. **16**: 121–125 (1890); Hume—Geol. mag. (3) **9**: 559 (1892); Carnegie—Spinifex and sand, p. 254–272 (1898); Hedin—Through Asia, vol. **1**, p. 485, 497 (1899); Fischer—Zs. Ges. Erdk. Berlin **35**: 411 (1900), Peterm. Mitt. Ergänzungsh. **133**: 122 (1900), Mitt. geog. Ges. Hamburg **18**: 154 (1902); Wright—Quart. jour. Géol. soc. **57**: 244–250 (1901); Cummins—Science gossip (n. s.) **8**: 161–166 (1901); Fountain—Mountains and forests of South America, p. 278–279 (1902); Russell—U. S. Geol. surv. Bull. **199**: 19 (1902); Ivchenko—Ann. géol. min. Russie **7**, I: 48, 50, 221–222 (1904); Gregory—Dead heart of Australia, p. 26, 120–121 (1906); Young—Survey notes (Egypt) **1**: 105–108 (1906); Craig—ibid. 357, 374 (1907); Huntington—Pulse of Asia, p. 148 (1907); Pearson—Nature **81**: 500 (1909); and authorities cited in following notes. Whirls will form not only in desert and steppe regions, but also over any bare surface subject to overheating by the sun (see the theory of origin outlined on the following pages). Thus they have been observed on paved streets, even in winter (Procter—Mon. weath. rev. **33**: 154 [1905]); on the burned-over moors of Germany (Miethe—Prometheus **10**: 795–796 [1899]); and in similar places elsewhere.

[c] Phil. mag. (3) **37**: 155–158 (1850), Jour. Asiat. soc. Bengal **19**: 390–394 (1850), **21**: 140–147, 264–269, 333–336 (1852), and Whirlwinds, etc. (1860). On the Indian whirls see also C. A. Gordon—Jour. Asiat. soc. Bengal **23**: 365–381 (1854); and Chatterjea—Proc. Asiat. soc. Bengal **1865**: 124–125.

[d] Quoted by Colladon—Arch. sci. phys. nat. Geneva (3) **2**: 35–42 (1879). See also report in Prometheus **8**: 347–348 (1896).

[e] See also the studies of Reye (Die Wirbelstürme, 1872), and of Weyher (Les tourbillons, 1887).

[f] Richthofen—China, vol. **2**, p. 550 (1877); Krebs—Globus **88**: 124 (1905).

[g] Humboldt—Aspects of nature, English ed. of 1850 (Sabine), vol. 1, pp. 36, 150. See also authorities cited on p. 80, note [b].

dry season even in the humid regions.[a] One of the most interesting phenomena in connection with dust whirls is the occurrence of systems of several whirls, each revolving rapidly about its own center and also moving about a common center in a more or less perfect circle a few rods in diameter. Such a system was noticed by Baddeley,[b] and others have been observed in North Carolina,[c] in Kansas,[d] and in South Africa.[e] Douglass,[f] and later the present writer have observed such systems in process of formation out of single large whirls of the usual type.

Baddeley[g] believed that dust whirls were of electrical origin and that the whirling column was an entity composed of "some form of electricity" or of "a permanent, indestructible form of imponderable matter hitherto undescribed." He was able to obtain charges from conductors inserted in the dust columns and from wires projecting into the atmosphere while dust clouds were passing.[h] In one case the current so obtained was sufficient to cause the deposit of silver from silver cyanide solution.[i] With advancing knowledge of the nature of electricity this theory has become untenable, and it seems probable that any electrical charges are effects rather than causes.[j] The mutual friction of innumerable fine particles suspended in very dry

[a] Instances in England are described by Taylor—Nature **38**: 415 (1888); Lovel—ibid. **40**: 174 (1889), **48**: 77 (1893); Upcott—Rept. Marlborough Coll. nat. hist. soc. **1901**: 90; Boys—Symons's met. mag. **39**: 134 (1904); and Clough—ibid. **40**: 104–105 (1905). On the continent: vom Rath—Ann. Phys. Chem. (Pogg.) **104**: 631–640 (1858); Quincy—Bull. Soc. sci. nat. Chalon-sur-Saône **28**: 183–186 (1902); "R. V."—Wetter **19**: 117–118 (1902); and Schiefer—ibid. **21**: 260–261 (1904). In Iceland: Ciel et terre **3**: 331 (1882). The dust-whirls of Mexico have been described by Virlet d'Aoust—Bull. Soc. géol. France (2) **15**: 129 et seq. (1857), Compt. rend. **83**: 890–892 (1876). The dust-whirls in semiarid North America are described by Nipher—Nature **18**: 488 (1878), **20**: 456 (1879); I. C. Russell—U. S. Geol. surv. Monogr. **11**: 154 (1886); "M."—Amer. met. jour. **2**: 285–286 (1885–6); Merrill—Eng. mag. **2**: 600–601 (1892); Walther—Verh. Ges. Erdk. Berlin **19**:52–65 (1892); and R. T. Hill—Eng. min. jour. **85**: 687 (1908).

[b] Whirlwinds, etc., p. 7 (1860).

[c] Kimball—Mon. weath. rev. **30**: 316 (1902).

[d] Mon. weath. rev. **27**: 111 (1899).

[e] Cummins—Science gossip (n. s.) **8**: 163 (1901). See also a description in Nature **25**: 291 (1882).

[f] Amer. met. jour. **11**: 405 footnote (1895).

[g] Works cited on p. 89, note [c]. The quotations are from "Whirlwinds and dust storms in India."

[h] Loci cit., especially the article in the Phil. mag., and p. 13, 32–33 and 53–54 in "Whirlwinds and dust storms." Electrical phenomena in connection with dust whirls have also been recorded by Peltier—Becquerel's Traitè expérimental électricité et magnétisme, vol. **6**, p. 184–189 (1840); and Cook—Quart. jour. Roy. meteor. soc. **9**: 141–143 (1883).

[i] Loc. cit. (Phil. mag. (3) **37**: 158).

[j] As was indeed suggested by Faraday in a letter to Baddeley in 1850. (Quoted in Baddeley's book, p. 4).

air would be likely to generate charges of considerable magnitude. That the electrical manifestations are merely incidental and not always present is further indicated by the inability of Pictet to obtain any charge from a well-developed whirl near Cairo.[a] It is now believed that dust whirls occur when the layer of air next to the ground becomes overheated by contact with a bare surface highly heated by the direct rays of the sun. This overheated air may remain for some time in an instable condition, but sooner or later something will disturb the equilibrium and the air will rush suddenly upward, leaving a space to be filled by the inrush of air from the sides. The mutual interference of these inrushing currents causes the whirl.[b] A whirl once formed by the action of the side currents will be maintained by the uprush of heated air constantly supplied by the hot surface. The spiral motion, once started, tends to maintain itself and the whirl acts as a chimney to remove the hot surface air to higher levels. Unless general atmospheric conditions (such as winds, etc.) interfere with its existence, the whirl will continue so long as the supply of overheated air is kept up. This explains the longer life of whirls in the hot deserts, and the brief continuance of those in humid and vegetation-covered areas where the ground surface is not so highly or so uniformly heated.

This theory is in accordance with the facts that whirls occur most often on level surfaces, bare of vegetation, and while the sun is shining; that the interior of the column is much hotter than the surrounding air;[c] and that they occur most frequently during calms.[d] Minute dust whirls have in fact been artificially produced by heating an iron plate on which fine silica had been sprinkled.[e] Great whirlwinds have also been several times noticed over fires where much air was rising in a body.[f] Similar whirlwinds occur

[a] Colladon—Arch. sci. phys. nat. Geneva (3) **2**: 39 (1879). Electrical phenomena have also been observed in connection with ordinary dust falls when no whirls are present. See Amaduzzi—Riv. sci. ind. **1901**: 61; and Chauveau—Ann. Soc. météor. France **51**: 77 (1903).

[b] On this theory of dust whirls, see Buchan—Handy book of meteorology, 2d ed., p. 306 (1868); Reye—Die Wirbelstürme, pp. 46–54 (1872); Davis—Elementary meteorology, pp. 36–37 (1894); etc.

[c] Pictet, in Colladon—Arch. sci. phys. nat. Geneva (3) **2**: 38–39 (1879); and Khanykov—Soc. géog. Paris Rec. voy. mém. **7**: 448–449 (1864).

[d] When winds are blowing the surface air is usually too much mixed and disturbed to become greatly overheated. Cf. Horner—Ann. Phys. (Gilbert) **73**: 95 (1823).

[e] Wood—Phil. mag. (5) **47**: 349 et seq. (1899). On the artificial formation of whirlwinds by the mutual interference of air currents, etc., see Vettin—Ann. Phys. Chem. (Poggendorf) **102**: 246–256 (1857); Hallier—ibid. **112**: 343–344 (1861), **114**: 657–660 (1861); and Weyher—Les tourbillons, 1887.

[f] Redfield—Amer. jour sci. **36**: 50–59 (1839); Olmsted—Proc. Amer. assoc. adv. sci. **4**: 361–365 (1850), Amer. jour. sci. (2) **11**: 181–187 (1851); Davis, quoted by Abbe—Mon. weath. rev. **34**: 164 (1906); and note in Pacific Rural Press **2**: 183 (1871).

above the craters of volcanoes during eruptions,[a] and over heated layers of fresh lava and ashes.[b]

According to the theory just explained, the air of the whirl moves in an ascending spiral, and the suspended dust which makes the whirls visible may be considered as derived from the soil and carried upward by the whirling air.[c] The rapid rotation of the lower end of the whirl furnishes the abrasive action necessary to loosen the soil. The heated air, carrying its load of dust, ascends in the spiral until it reaches the point where its density is the same as that of the surrounding air, when it spreads out more or less horizontally, leaving the dust which it carries to fall earthward and to be blown here and there by the winds. In hot climates, where the overheating of the surface air is considerable, whirls may reach great heights, and since they are able to carry more and coarser material than can be handled by ordinary winds, they are very important agents in supplying dust to the winds and in enabling the latter to attack the surface. The erosive activity of whirlwinds has been pointed out by Brunhes,[d] and Virlet d'Aoust[e] mentions the existence, on the slopes of the Mexican mountains, of soils composed of material lifted by whirlwinds from the plains below.

Tornadoes and waterspouts are apparently similar to the dust whirls just described, but have probably a different origin.[f] It is believed that these storms originate in the higher levels and grow downward to the earth. The aspirating action is not so marked as in the dust whirls, and the great damage done by these storms is due not to it but to the violence of the whirling wind and the explosive action of imprisoned air in houses, etc., momentarily within the area of greatly reduced pressure at the center of the whirl. The water supposed to be sucked up by waterspouts is probably derived from the clouds and not the sea, since it has been found to be fresh.[g] Tornadoes always occur in connection with cyclones[h] and usually

[a] Redfield—Amer. jour. sci. **36**: 57 (1839); von Seebach—Abh. K. Ges. Wiss. Göttingen **13**: 57 (1868); Mack—Met. Zs. **18**: 250–256 (1901).

[b] J. Roth—Der Vesuv und die Umgebung von Neapel, p. 130 (1857); Bailleul—Compt. rend. **31**: 8 (1850).

[c] Contrary to the opinion of Faye (Compt. rend. **83**: 766, 893 [1876]), who considered the dust whirl as *descending* and the lifting of dust due to the rise, outside the whirl, of masses of heated air which had descended inside and escaped at the bottom.

[d] Compt. rend. **135**: 1133 (1902); Mem. Accad. Nuovi Lincei (5) **21**: 129–148 (1903). See also Walther—Wüstenbildung, p. 132 (1900).

[e] Bull. Soc. géol. France (2) **15**: 129 et seq. (1857).

[f] On the nature of tornadoes, see Reye—Die Wirbelstürme, (1872); Davis—Elementary meteorology, pp. 271–284 (1894), and other text-books of meteorology.

[g] Davis—Elementary meteorology, p. 283 (1894).

[h] The word "cyclone" is used in its technical sense to designate the circular storms of wide area (100 to 500 miles). The popular application of the word to all violent storms, and especially to the above-described tornadoes, is incorrect.

in a certain quadrant. They are probably in some way secondary manifestations of the larger storms set up by the various convectional currents occurring within it.

It is of course possible that a tornado might occur over a desert or similar exposed surface, and if so it would probably move about a good deal of soil material, but the absence of any rising current precludes the lifting action which is shown by true dust whirls. The latter are distinguished from tornadoes by their dependence on local surface conditions rather than on those of the atmosphere in general. They are independent phenomena, not connected with any general storm, travel much less rapidly, and are not nearly so violent.[a]

The momentary dust eddies common on windy days in streets and fields are due simply to the wind blowing around obstructions, or to the mutual interference of opposing currents. Such eddies are of constant occurrence in the wind and become visible whenever they happen to be in such relation to attackable deposits as to be able to pick up dust. They are probably, as already pointed out, of considerable assistance in enabling the wind to acquire and support its load of solid material.

EUROPEAN DUST FALLS.

The best known and most studied of all dust storm phenomena are the falls of reddish dust which occur in southern and central Europe, sometimes alone, sometimes with rain or snow. The dust occasionally fills the atmosphere so completely that dry fogs are produced, and these phenomena are sufficiently common off the west coast of northern Africa to have earned for this part of the ocean the title of the "dark sea."[b] From the apparent connection of this oceanic dust with the trade winds comes its German name of "Passatstaub" (trade-wind dust). In English it is usually called sirocco dust. Falls of this dust have been known in Europe and along the Mediter-

[a] Baddeley (Phil. mag. (3) **37**: 158 [1850]) mentions a "dust whirl" which was strong enough to crack brick walls and uproot trees. It is probable that this was a tornado and not a dust whirl. Doctor Baddeley did not see it himself. Such violence on the part of a true dust whirl would be almost inconceivable. Ivchenko has, however, reported whirls which were violent enough to upset a man (Ann. géol. min. Russie **8**, I: 139 [1906]).

[b] Schmid—Lehrbuch der Meteorologie, p. 796 (1860). The dust fogs of this region were noted by the Arabian geographer Edrisi in the twelfth century (Tchihatchef—Rept. Brit. assoc. **1882**: 360). For later accounts see Darwin—Quart. jour. Geol. soc. **2**: 26–30 (1846), also summarized in his Journal of researches, p. 5, ed. of 1901; Hellmann—Monatsb. K. Preuss. Akad. Wiss. Berlin **1878**: 364–403; Dinklage—Annalen Hydrog. **14**: 69–81, 113–123 (1886), **16**: 145–149 (1888), **17**: 450–454 (1889), **19**: 313–318 (1891), **22**: 140–143 (1894), **26**: 246–254 (1898), **29**: 30–37 (1901), **31**: 430–438 (1903); Krebs—Beiträge Geophysik **8**: 7–42 (1906); M. Jentzsch—Annalen Hydrog. **37**: 373–376 (1909). Similar dust fogs occur off the coast of China, near Australia, and elsewhere.

ranean since the earliest times. They are mentioned by Homer,[a] Virgil,[b] and Livy,[c] and Ehrenberg [d] cites a number of well authenticated cases in the first three or four centuries before Christ. The first known scientific description is that of Wendelin.[e] There is no reason to believe that they occurred any less frequently in former times than they do to-day, but owing to the incompleteness of the records only a small proportion of the older occurrences are now known. Ehrenberg's first [f] historical list gave 340 occurrences down to 1847. This was supplemented and brought down to 1870 by another list [g] giving 193 occurrences. Many falls have occurred since 1870 and have been noticed in the literature.[h] The two great falls of

[a] Iliad, Book **11**, lines 52–54; Book **16**, lines 459–460.

[b] Æneid, Book **4**, line 454.

[c] Historiae, Book **3**, chap. 10; Book **10**, chap. 31.

[d] Passatstaub und Blutregen, p. 59 et seq. Professor Ehrenberg's investigations of sirocco dust are the most extensive on record, the results being published in the Abhandlungen and the Monatsberichte of the Berlin Academy from 1844 to 1875. The earlier of these investigations (up to 1849) were collected and published in book form in 1849, under the title "Passatstaub und Blutregen." This work contains his theory of the origin of sirocco dust (see p. 90 below) and the observations upon which it was based. His later investigations (1848 to 1871) were collected and summarized in an article entitled "Uebersicht der seit 1847 fortgesetzten Untersuchungen über das von der Atmosphäre unsichtbar getragene reiche organische Leben," and published in the Abh. K. Preuss. Akad. Wiss. Berlin **1871**: 1–150, 233–275.

[e] Pluvia purpurea bruxellensis (1646).

[f] Passatstaub und Blutregen, pp. 59–127 (1849).

[g] Abh. K. Preuss. Akad. Wiss. Berlin **1871**: 14–60. Many occurrences are cited in the early chronicles and 83 of them have been noted by Hennig—Katalog bemerkenswerter Witterungsereignisse (1904).

[h] Partial lists are given by Silvestri (1869–1872)—Atti. Accad. Gioenia Catania (3) **12**: 137 (1878); Macagno and Tacchini (1870–1879)—Ann. meteor. ital. (2) **1**: 72 (1879); Denza (1862–1869)—Compt. rend. **70**: 534 (1870); Passerini (1813–1889)—Atti. R. Accad. Georg. econ.-agr. Florence (4) **24**: 150 (1901); Trabert and Valentin (1864–1901)—Jahrb. Naturw. **17**: 212–213 (1901–2); and Galli (1813–1903)—Mem. Accad. Nuovi Lincei (5) **21**: 404–406 (1903). Many occurrences are cited in the columns of Wetter, the Meteorologische Zeitschrift, the Annalen der Hydrographie, Ciel et terre, and other meteorological periodicals.

Literature (not elsewhere cited) on European falls of sirocco dust (and possibly other materials) is given in the bibliography under Abels, Alvarez, Ankert, Archenhold, Assmann, Barač, Barfod, Becke, van Bemmelen, Bijelic, Boroi, van den Broeck, Campini, Canaval, Casali, Chauveau, Chéneau, Chladni, Choffat, Cittadella-Vigodarzere, Cohn, Coles, Courty, Cramer, Daubrée, Denza, Deschmann, Dessau, Dove (Gesetz der Stürme, p. 69), Eredia, Evans, Finckh, Flammarion, Flores, Forel, Fournet, Friedel, Fryer, Gaberel, Galli, Ginestous, Gottsche, Gregorio, Hampe, Hann, Häpke, Hellmann, Hepworth, Hübner, Ippen, Jaubert, Jeremiah, Jörschke, Jussieu, Karrer, Kittel, C. Knab, Korostelev, Krebs, Lais, Langell, Leopold Ferdinand, Leps, Lorié, Lüdeling, MacCarthy, Marinelli, Mascart, Mazelle, Meinardus, Meunier, Millosevich, H. C. Moore, Moureaux, Müttrich, Nell, Nicati, Ossig, Palmeri, Palmieri, Paris and Roncali, de Parville, Passerini, Paudler, Perry-Coste, Peschier, Phipson, Pichler, Prettner, Prior, Prohaska, Ragona, Reissek, Riccò, Richter, Róna, Rücker, M. Schuster, Schwarz, Schwedoff, Sébillant, Secchi, Seeland, Seidl, Silvestri, Souza-Brandão, Sprenger, Stefano, Stiglleithner, Svoboda, Symons's met. mag., Tacchini, Tacquin, Tarry, Teisserenc de Bort, Vacher, Valderrama, Vivenot, West, A. S. White, Wilbrand, Yates, and Zona.

the last decade were those of March 9 to 12, 1901; and of February 22 to 23, 1903. The former has been discussed in an admirable monograph by Hellmann and Meinardus,[a] and also by Valentin [b] and Vanderlinden.[c] The fall of February, 1903, has been discussed by Herrmann,[d] Hellmann,[e] Mill and Lempfert,[f] and Vanderlinden.[g]

EARLY THEORIES REGARDING EUROPEAN DUST FALLS.

During the Middle Ages the dust was supposed to be of extraterrestrial origin,[h] and the falls were regarded with great terror, which was accentuated by the bloodlike appearance of the rain drops charged with dust.[i] Sementini [j] gives a graphic account of the fright of the people during a fall of dust at Gerace, in Calabria, Italy, on March 14, 1813, on which occasion the popular terror was intensified by the accidental breaking out of a fire which brought conviction that the end of the world was at hand.

The cosmic theory was succeeded by that of Ehrenberg[k] who believed that there existed in the upper atmosphere a mass of permanently suspended living matter (mainly diatoms) in microscopic particles, and that dust falls occurred whenever this upper stratum was so distorted as to come in contact with the land surface. Ehrenberg was led to adopt this view because he found in the various samples of fallen dust which came under his examination diatoms representing every part of the world, especially some which he considered characteristic of South America. Some of these diatoms were living, and he therefore felt bound to assume that they came from an aerial ocean of life which was continually being replenished by organisms lifted by air currents from all parts of the earth's surface. His especial interest in the organic remains of the air dust blinded him to

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[a] "Der grosse Staubfall vom 9 bis 12 März 1901 in Nordafrika, Süd- und Mitteleuropa," Abh. K. preuss. meteor. Inst. **2**, No. 1, 1901.

[b] Sitzungsb. Kaiserl. Akad. Wiss. Vienna **111**, IIa: 727–776 (1902).

[c] Ciel et terre **22**: 257–262 (1901).

[d] Annalen Hydrog. **31**: 425–438, 475–483 (1903).

[e] Meteor. Zs. **20**: 133–135 (1903).

[f] Quart. jour. Roy. meteor. soc. **30**: 57–91 (1904).

[g] Ciel et terre **24**: 44–59 (1903).

[h] See Arago—Astronomie populaire, vol. **4**, pp. 208–216 (1857); and Quetelet—Physique du globe, chap. 4, p. 322 (1861).

[i] Ehrenberg has collected the accounts given by the early chroniclers of the appearance of bloody rain, blood on articles of food, etc. (Monatsb. K. preuss. Akad. Wiss. Berlin **1850**: 215–246). Many of these appearances are to be ascribed to bacterial action, etc., and not to dust falls. It is claimed that rain which fell at Oppide Mamertina, Italy, May 15, 1890, actually contained true blood, believed to be from birds, Passerini—Atti. R. Accad. econ.-agr. Georg. Florence (4) **24**: 150 (1901).

[j] Jour. Chem. Phys. (Schweigger) **14**: 130–132 (1815).

[k] Passatstaub und Blutregen, pp. 57, 163 et seq. (1849).

the indications of terrene origin offered by the inorganic constituents, and his observations of the occurrence in European air dust of diatoms apparently characteristic of South America and other far countries may be explained by assuming that these forms actually exist in Europe or Africa, but have never been reported, although, for that matter, there is no insuperable objection to believing them actually carried, though perhaps in small number, from South America or even places still farther away. The atmosphere always contains a great deal of permanently suspended dust, and diatom fragments, being light in proportion to their surface area, are likely to remain long in suspension and be carried far and wide. It is quite possible that any air dust collected in Europe would contain a few particles, diatomaceous and otherwise, which had come from other continents. The evidence is now conclusive that the major part of the typical sirocco dust is from the desert of the Sahara.[a]

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[a] It is necessary, of course, to except local showers of material derived from the neighborhood, and the part of all fallen dust which is of local origin. (See p. 106.) Showers of material other than sirocco dust also occur occasionally, as, for instance, pollen from pines and similar trees. On such occurrences see Göppert—Ann. Phys. Chem. **21**: 550–578 (1831); Kaemtz—Meteorology—English trans. by Walker, p. 465 (1844); Amer. jour. sci. **39**: 399 (1840), **42**: 195–197 (1842); Arago—Oeuvres complétes, vol. **12**, p. 469 (1859); Ernst—Nature **4**: 68 (1871); Bureau and Poisson—Compt. rend. **83**: 194–196 (1876); Carpenter—Nature **20**: 195–196 (1879); A. Wilson—ibid., 266–267 (1879); Mon. weath. rev. March, 1879, p. 16; Tissandier—La Nature **1887**, II: 62; C. Turner—Nature **66**: 157 (1902); Forel—Bull. Soc. vaud. sci. nat. **39**: L (1903); Sci. Amer. **88**: 243 (1903); Jaubert—Ann. Obs. Montsouris **5**: 333 (1904). A fall of lichens with rain has been reported from Persia by De Candolle—Géographie botanique raisonnée, vol. **2**, pp. 614–615 (1855). Small live fish are said to have fallen at Madras, India (Harriott—Struggles through life, vol. **1**, pp. 141–142 [1809]); at Singapore (Castelnau—Compt. rend. **52**: 880–882 [1861]); at Winter Park, Fla., in June, 1893 (T. R. Baker—Science **21**: 335 [1893]); and at Tillers Ferry, S. C., in 1901 (Mon. weath. rev. **29**: 263 [1901]). There is a well-authenticated case of the fall in the Gothard Alps on August 30, 1870, of a considerable quantity of crystals of common salt, one of which weighed 0.76 gram. (Kenngott—Viertelj. naturf. Ges. Zurich **15**: 377–379 [1870]; Vogler—Flora **89**: 86–89 [1901]). Falls of terrestrial pebbles and small stones weighing from a fraction of a gram to several grams are recorded by Phipson—Rept. Brit. Assoc. **1864**, Trans. secs.: 37; Nordenskiold—Öfvers. K. Vet.-akad. förh. **41**, VI: 3–15 (1884); Meunier—Compt. rend. **113**: 100–101 (1891); and Rollier—Actes Soc. helv. sci. nat. **90**, I: 248–258 (1907). A turtle 6 inches by 8 inches and a stone fragment ½ inch by ¾ inch, both incased in ice, fell at Vicksburg, Miss., on May 11, 1894 (Abbe—Mon. weath. rev. **22**: 215 [1894]).

Certain cases of red or pink colored snow are caused by the growth of microscopic plants, especially the *Protococcus nivalis*. See de Saussure—Jour. nat. phil. chem. arts **1**: 511–513 (1797); Peschier—Bibliotheque univ. **12**: 259–265 (1819); Bauer—Quart. jour. sci. **7**: 222–229 (1819); Annal. chimie **12**: 72–88 (1819); Bauer—Phil. trans. **110**: 165–173 (1820); Kaemtz—Meteorology, English trans. by Walker, pp. 455–456 (1844); A. P. de Candolle—Verhandl. Schweizer Ges. **1825**: 26–28; Darwin—Journal of researches, p. 327, ed. of 1901; L. J. Agassiz—Rept. Brit. assoc. **1840**, trans.: 143; Arago—Oeuvres complétes, vol. **12**, p. 472–488 (1859); L. Fischer—Mitth. naturf.

THE SAHARAN ORIGIN OF SIROCCO DUST.

The Saharan origin of sirocco dust was suggested by Lavagna [a] in connection with a discussion of the fall of November 27–28, 1814, and probably by even earlier writers, but the suggestion was opposed by Ehrenberg, and has gained general acceptance only within the last twenty-five years.[b] The character of the dust itself suggests a desert origin, as it consists very largely of very fine splinters of quartz and a still finer claylike dust often gathered into flocks or aggregates [c] which is probably the final débris from the disintegration of the feldspathic and similar minerals. Mica flakes are found in nearly all samples, as is to be expected in view of their high surface mass ratio and consequent facile flotation. Other minerals frequently present, though always in small quantity, are feldspars (orthoclase and probably plagioclase also), calcite, magnetite, zircon, rutile, tourmaline, hornblende, epidote, and apatite. Pyrite, hematite, chromite, ilmenite, garnet, augite, talc, and gypsum have been occasionally found.[d] The reddish color is probably due to ferru-

Ges. Bern **1867**: 210–213; Wittrock—Botaniska not. **1883**: 76–79; van Haast—Nature **30**: 55 (1884); and notes in Nature **63**: 471–472 (1901); and Symons's meteor. mag. **36**: 33–34 (1901).

Black and gray rains and snows are sometimes caused by the presence in the atmosphere of much smoke from industrial establishments, great fires, etc. See Arago—Oeuvres complétes, vol. **12**, p. 466 (1859); W. N. Shaw—Jour. San. inst. **23**: 323 (1902). Many notes of occurrences are given in the columns of Nature.

One of the most interesting of the early theories regarding the nature of sirocco dust is the statement of Meyer and Stoop (Ann. gén. sci. phys. nat. **2**: 269–271 [1819]) that the red rain which fell near Bruges on November 2, 1819, was colored by the presence of a comparatively large quantity of dissolved chloride of cobalt. This is highly improbable, and the error is probably to be ascribed to faulty analyses. The rain may have contained traces of cobalt (see p. 121 below) but hardly more than traces.

[a] Giorn. fis. chim. stor. nat. (2) **1**: 32–36 (1818).

[b] It was strongly opposed by Silvestri in 1876 (Atti Accad. Gioenia Catania (3) **12**: 146–151 [1878]); and by Casali even so late as 1901 (Resto del Carlino, Bologna, April 15–16, 1901, through Flores—Boll. Soc. geol. ital. **22**: 81 [1903]).

[c] Lais—Nature **16**: 197–198 (1877); Editorial—Mon. microscopic jour. **18**: 159 (1877); Max. Schuster—Sitzungsb. Kaiserl. Akad. Wiss. Vienna **93**: 84 (1886); Camerlander—Jahrb. geol. Reichsanst. **38**: 289 (1888).

[d] For mineralogical examinations of sirocco dust see Dufrénoy—Compt. rend **13**: 62–63 (1841); Cannobio—ibid., 215–219; Reissek—Ber. Mitt. Freunden Naturw. **4**: 153 (1848); Hellmann—Monatsb. K. Preuss. Akad. Wiss. Berlin **1878**: 402; Silvestri—Atti Accad. Gioenia Catania (3) **12**: 123–151 (1878); Macagno and Tacchini—Ann. meteor. ital. (2) **1**: 68–69 (1879); von Lasaulx—Tschermak's min. Mitth. (n. s.) **3**: 528 (1880); Max. Schuster—Sitzungsb. Kaiserl. Akad. Wiss. Vienna **93**: 83–85 (1886); Camerlander—Jahrb. geol. Reichsanst. **38**: 288, 291, 297–298 (1888); Ginestous—Compt. rend. **123**: 1093–1094 (1896); Dinklage—Annalen Hydrog. **26**: 253 (1898); Hellmann and Meinardus—Der grosse Staubfall, p. 54 et seq., 90 (1901); Becke—Anz. Kaiserl. Akad. Wiss. Vienna **38**: 107–109 (1901), Met. Zs. **18**: 318–321, 462–463 (1901); Achiardi—Atti R. accad. econ.-agr. Georg. Florence (4) **24**: 143–147 (1901); Früh—

ginous matter. Diatoms and other organic materials are not infrequently present in considerable amount.

It is probable that the rarer minerals mentioned belong largely, if not entirely, to the local material which is necessarily intermixed with all eolian deposits, for if these minerals do exist in the true African dust (as is not impossible) it is probable that they are in the form of particles far too fine for detection and determination. They form the claylike and apparently amorphous portion which is always present.

TABLE V.—*Chemical analyses of sirocco dust.*

Number	I.[a]	II.[b]	III.[b]	IV.[c]	V.[d]	VI.[e]	VII.[f]	VIII.[g]
Locality	Tyrol.	Palermo.	Palermo.	Naples.	Taormina, Sicily.	Lamberhurst, England.	Tunis, Africa.	Desert dust from Biskra.
Date of fall	Mar. 31, 1847.	Apr. 14, 1874.	May 17, 1879.	Mar. 10, 1901.	Mar. 19, 1901.	Feb. 22, 1903.	Mar. 10, 1901.	
SiO_2	15.90	65.04	64.00	49.40	42.48	50.50	73.45	68.90
Al_2O_3	9.58	.40	.24	21.52	21.19	20.20	2.36	.09
Fe_2O_3	17.42	2.45	1.56	7.65	7.95	7.23	4.50	1.53
CaO	16.90	6.80	7.00	7.08	8.16	9.50	5.25	7.37
MgO	3.26	3.16	2.58	.....	2.89	2.43	.....	2.08
K_2O	3.29	1.96	1.90	2.96	3.56	2.53	.....	1.32
Na_2O	.....	.02	1.17	2.84	3.39	1.28	.....	.79
P_2O_5	.....	1.12	1.16	.22	.....	.....	.....	Trace.
CO_2	33.49	14.41	13.69	3.77	4.81	6.71	6.48	13.28
Loss on ignition	4.15	21.97	21.98	8.19	23.49	20.36	9.50	7.22

[a] Oellacher—Wiener Ztg., June 2, 1847, quoted by Ehrenberg, Passatstaub und Blutregen p. 27 (1849).
[b] Macagno and Tacchini—Ann. meteor. Ital. (2) **1**: 66 (1879).
[c] Palmeri—Rend. R. Accad. sci. fis. Naples (3) **7**: 157 (1901).
[d] Analysis by Simmonds, quoted by Thorpe—Nature **68**: 222 (1903). An analysis of the material soluble in hydrochloric acid is also given. Cf. also Judd—Nature **63**: 514 (1901).
[e] Thorpe—Nature **68**: 54 (1903). Analysis of material soluble in hydrochloric acid is also given.
[f] Bertainchand—Compt. rend. **132**: 1153 (1901).
[g] Analysis by Macagno, quoted by Tacchini—Trans. R. Accad. Lincei (3) **7**: 135 (1883).

The chemical composition of sirocco dust is also in perfect accord with the Saharan hypothesis, as is apparent from a comparison of analyses 1 to 6 of Table V with analysis 7 of the same table, which represents the dust which fell in Tunis, Africa, in March 1901, and

Met. Zs. **20**: 174 (1903); Basarow—La Nature **31**, II, nouv. sci.: 6 (1903); Forel—Bull. Soc. vaud. sci. nat. (4) **39**: xxvii (1903); Mill and Lempfert—Quart. jour. Roy. meteor. soc. **30**: 74–75 (1904); Prinz—Ciel et terre **24**: 25, 80, 293–300 (1903).

For purposes of comparison there is appended a mineralogical analysis by Thoulet of sand from near Wargla, in the Sahara (Bull. Soc. min. France **4**: 268 [1881]):

	Per cent.
Quartz	89.46
Feldspar	9.47
Calcium carbonate and clay	.67
Chloride of potassium and sodium	.17
Hematite, chromate, garnet, olivine, amphibole, pyroxine, etc.	.23
	100.00

with analysis 8, which represents the fine material separated by water elutriation from a sample of desert sand collected at Biskra, in the Sahara. In order to make them of value for comparison all the analyses are expressed in percentages of the ignited weight, and, where necessary, they have been recalculated to bring them to this basis. The percentage of loss on ignition is given separately in the last line of the table. The analyses of European sirocco dust are as uniform as could be expected when allowance is made for local admixture; thus the low silica in No. 1 is due to the large amount of calcium carbonate, which in turn is probably due to the presence of calcareous material derived from the neighborhood. The most noticeable and surprising difference between the Sahara dust (analysis 8), and that fallen in Europe is in the content of alumina. It would seem that the amount of this constituent present in European dust must have its source elsewhere than in the desert sands. It may perhaps come from laterite deposits south of the desert,[a] but it is more probably due to the local admixture of kaolin clays. It is noticeable that the analyses of Palermo dust (Nos. 2 and 3) correspond almost exactly, even in alumina content, to the analysis of Sahara dust. From the situation of Palermo it is to be expected that dust fallen there would be rather unusually free from local admixture, and likely to represent the true African material with greater exactness than would dust fallen farther north. The Tunis analysis (No. 7) is remarkable only for the high silica. It is probable that the European dust is lower in this constituent because of its removal by elutriation during translocation. The finest material being more largely nonsiliceous the process of air sorting would tend to eliminate silica, and the material would be expected to become more and more siliceous the nearer the point of collection to the point of origin. Material collected at the place of origin ought therefore to be the most siliceous of all, and from this point of view the silica content shown by analysis 8 may seem too low. However, this dust was removed from the desert sand by water, not by air, and is therefore likely to be more largely composed of the finer particles. Water elutriation permits of much more accurate separations than does the air elutriation, which takes place in the more or less variable currents of natural winds. The dust of analysis 8 may have undergone in water a sorting equivalent to that which would be produced by a long air voyage.

[a] This could be settled by an examination of the dust for free alumina, but the analytical methods are unfortunately so unsatisfactory that the results are inconclusive. See Thorpe—Nature **68**: 223 (1903). On the relation of sirocco dust to laterite see Doelter—Mitth. naturw. Ver. Steiermark **38**: xlvii-xlviii (1901); and Ippen—Centbl. Min. **1901**: 578–582.

In Table VI are given the maximum, minimum, and average values of the principal constituents as calculated from twenty-six of the best European analyses found in the literature. Analyses 1 to 7, inclusive, of Table V are included. As before, all analyses are reduced to percentages of the ignited weight, and the per cent loss of weight on ignition is given separately. No great accuracy can be ascribed to these figures. The analyses were made by many different methods and many of them are incomplete. The number of determinations entering into the average for each constituent is given in the first column of the table.

TABLE VI.—*Average chemical composition of sirocco dust.*[a]

Constituent.	No. of analyses.	Maximum.	Minimum.	Average.
SiO_2	26	73.45	15.90	57.5
Al_2O_3	19	28.50	.24	14.3
Fe_2O_3	19	17.42	1.56	8.0
CaO	24	16.90	0	8.3
MgO	17	3.77	Trace.	1.7
K_2O	9	3.65	1.02	2.5
Na_2O	8	3.39	.02	1.7
P_2O_5	3	1.16	.22	.8
CO_2	20	33.49	3.77	12.4
Loss on ignition	24	36.40	4.00	16.5

[a] The analyses used in compiling this table are the following:
Analyses I to VII of Table V.
Dust fallen on ship on the Atlantic. O. W. Gibbs—Ann. Phys. Chem. (Poggendorf) **71**: 567 (1847).
Fallen at Idria, Italy, April 14, 1813. Vauquelin—Ann. chim. phys. (2) **39**: 438-442 (1828).
Fallen at Verpilliere, France, October 16, 1847. Du Pasquier—Mém. Acad. sci. Lyon **1**: 5-16 (1845).
Same fall as last, but evidently another analysis. Quoted by Ehrenberg—Passatstaub und Blutregen, p. 43 (1849).
Fallen at Graubünden, Switzerland, Feb. 4, 1851. Will—Jahresb. reinen Chém. **1851**: 883.
Five analyses of dust fallen at Palermo, Sicily, 1870 to 1878, belonging to the same set as Nos. II and III of Table V. Macagno and Tacchini—Ann. meteor. ital. (2) **1**: 66 (1879).
Fallen at Naples, Italy, Feb. 25, 1879. Analysis by Scacchi, quoted by Palmeri—Rend. R. Accad. sci. fis. Naples (3) **7**: 161 (1901).
Fallen on Elba, Feb. 25, 1879. Roster—l'Orosi **8**: 75 (1885).
Fallen at Fiume, Hungary, March 10, 1901. Hellmann and Meinardus—Der grosse Staubfall, p. 69 (1901).
Fallen at Florence, Italy, March 10, 1901. Passerini—Atti R. Accad. econ.-agr. Georg. Florence (4) **24**: 142 (1901).
Fallen in the Klausthal, Germany, March 19, 1901. Hampe—Naturw. Runds. **13**: 285-287 (1898).
Two samples of that fallen at Swansea, England, Feb. 22, 1903. Flett—Quart. jour. Roy. meteor. soc. **30**: 77 (1904).
Fallen at Buckfastleigh, England, Feb. 22, 1903. Earp—Nature **67**: 415 (1903).
Further analyses not included in Tables V and VI are given by Palmeri and by Macagno and Tacchini (loci citati) and by the following: Döbereiner—Jour. Chem. Physik (Schweigger) **9**: 222 (1813); Sementini—Giorn. fis. chim. stor. nat. (2) **1**: 23-32 (1818); Canobbio—Compt. rend. **13**: 215 (1841); Dufrénoy—Compt. rend. **15**: 580-584 (1842); Ehrenberg—Passatstaub und Blutregen, p. 47 (1849); Bouis—Compt. rend. **56**: 974 (1863); Silvestri—Ann. sci. ind. **6**, I: 107-108 (1869), quoted by Tarry—Compt. rend. **70**: 1371 (1870); Nicati—Bull. Soc. vaud. sci. nat. **10**: 285 (1869); Camerlander—Jahrb. geol. Reichsanst. **38**: 293 (1888); Nordenskiöld—Met. Zs. **11**: 216-217 (1894); von John—Verh. geol. Reichsanst. **1896**: 259; Hampe—Naturw. Runds. **13**: 285-287 (1898); Dinklage—Annalen Hydrog. **26**: 254 (1898); Clerici—Boll. Soc. geol. ital. **20**: clxix-clxxviii (1901), **21**: xxix note (1902); Baraõ—Verh. naturf. Ver. Brünn **40**: 48-54 (1901); Svoboda—Zs. landw. Versuchsw. Oest. **4**: 630-631 (1901); Meunier—Compt. rend. **132**: 895 (1901); Ippen—Centbl. Min. **1901**: 581; Forel—Verh. Schweiz. naturf. Ges. Aarau **85**: 63 (1902); Prometheus **16**: 254 (1905). Qualitative analyses (lacking quantitative data) have been published by Fabroni—Ann. chim. phys. **88**: 146-152 (1813); Max. Schuster—Sitzungsb. Kaiserl. Akad. Wiss. Vienna **93**: 87-104 (1886); Böhm—Met. Zs. **18**: 278-279 (1901); Walther—Naturw. Wochens. **18**: 603 (1903); Herrmann (analysis by Lam)—Annalen Hydrog. **31**: 477 (1903); and E. G. Clayton—Proc. Chem. soc. London **19**: 101-103 (1903).

The argument of Ehrenberg [a] that the sirocco dust can not be from the Sahara because it is red, whereas the desert sands are white, loses its force in the light of what was said on page 37 concerning deflation

[a] Passatstaub und Blutregen, p. 30 (1849).

from deserts. The sands contain no dust, because all dust has been blown away, and similarly they are white because the red and yellow material has likewise been removed by the wind. The reddish minerals are mainly hydrated iron compounds derived from the weathering of ferro-magnesian minerals and are therefore very susceptible to fine division and sequent removal by the wind. Walther[a] has observed that the dust carried by temporary rills of water in the desert is red,[b] and the dust, the analysis of which is given as No. 8 in Table V, was reddish yellow.

But the most conclusive evidence regarding the Saharan origin of the sirocco dust is derived from meteorological sources. It has been found possible by the use of barometric data to map the path of several of the dust-bearing storms and trace them back to a point of origin in northern Africa. This was attempted in a rough way by Tarry[c] for the storms of March 10, 1869, and February 13, 1870, but his results were incomplete and somewhat open to question.[d] The storms of March 9 to 11, 1901, and of February 22 to 23, 1903, have, however, been conclusively traced to the Sahara.[e] These conclusions are confirmed by the observation[f] that dust falls are usually accompanied by winds drier and hotter than are normal in European localities, thus suggesting their origin in the warmer regions to the south. It seems as well that there is a tendency for dust falls to occur most frequently in those years when the Sahara is driest.[g] As a result of the cumulative force of the facts above outlined the Saharan origin of the sirocco dust is now generally regarded as beyond question.[h]

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[a] Denudation in der Wüste, p. 494 (1891). There is a reddish loessial deposit near Biskra (Grund—Sitzungsb. Kaiserl. Akad. Wiss. Vienna **115**: 545 [1906]).

[b] The same observation has been made several times by the present writer in the deserts of North America.

[c] Compt. rend. **70**: 1043–1046, 1369–1372 (1870).

[d] For a criticism see Camerlander—Jahrb. geol. Reichsanst. **38**: 309 (1888).

[e] On the storm of March, 1901, see Hellmann and Meinardus—Der grosse Staubfall, p. 32 et seq. (1901); Köppen—Annalen Hydrog. **31**: 45–48 (1903); and Krebs—Frankfurter Zeitung, March 18, 1901, abstracted in Globus **84**: 182 (1903). On the storm of February, 1903, see Schiefer—Wetter **20**: 259–261 (1903); Vanderlinden—Ciel et terre **24**: 49–59 (1903); and Mill and Lempfert—Quart. jour. Roy. meteor. Soc. **30**: 57–91 (1904).

[f] Mill and Lempfert—loc. cit. in last note; Tacchini—Ann. meteor. ital. (2) **1**: 81–88 (1879); Forel—Bull. Soc. vaud. sci. nat. (4) **39**: xxvii (1903).

[g] Krebs (Globus **84**: 183–184 [1903]) has made comparisons from 1782 to 1898, which seem to bear this out. His dates for dry years in the Sahara are calculated from the data of Brückner (Klima-Schwankungen seit 1700 [1890]).

[h] A résumé of considerations leading to this conclusion is given by Hellmann and Meinardus—Der grosse Staubfall, pp. 79–81, 89–92 (1901). See also, in addition to the authorities already cited: Denza—Ann. sci. ind. **7**, II: 640–648 (1870); Roster—l'Orosi **8**: 76 (1885); Früh—Met. Zs. **20**: 175 (1903); and Forel—Compt. rend. **136**: 636–637 (1903), Bull. Soc. vaud. sci. nat. (4) **39**: xxxiv–xxxv (1903).

QUANTITY OF DUST DEPOSITED IN EUROPE.

The quantity of dust which fell on March 9 to 12, 1901, was measured at various places in Europe, and the measurements have been collected by Hellmann and Meinardus.[a] They range from 11.23 grams to 1 gram per square meter (31.1 tons to 2.9 tons per square mile), the values being largest in southern Europe and decreasing toward the north. Some measurements which have been made on other falls are given in Table VII.

TABLE VII.—*Quantity of dust deposited on unit area in various European dust falls.*

Date.	Place.	Weight of dust.	
		Grams per square meter.	Tons per square mile.
Oct. 16, 1846 [a]	Southeastern France	0.63	1.8
Mar. 31, 1847 [b]	Tyrol	2.0	5.7
1859 [c]	Westphalia	30.0	85.8
Feb., 1862 [c]	Salzburg, Austria	.08	.24
Mar. 24, 1869 [c]	Carniola, Austria	5.0	14.3
Mar. 19, 1901 [d]	Taormina, Sicily	2.7	7.7

[a] Chauveau—Ann. Soc. météor. France 51: 72 (1903). The quantity of this fall as measured at Valence, France, is given by Ehrenberg (Passatstaub und Blutregen, p. 42) as 0.75 gram per square meter, or 2.1 tons per square mile.

[b] Ehrenberg—Passatstaub und Blutregen, p. 26. Given as 103 grams per square fathom.

[c] Chauveau—loc. cit. in note [a] above.

[d] Rücker—Nature 63: 514 (1901), 64: 30 (1901). Three determinations were made and gave 1.5, 2.6, and 3.5 grams per square meter, respectively. Weighting the determinations according to the probable accuracy of each, 2.7 grams per square meter was obtained as a probably true average.

The areas covered by the different falls vary widely. Falls occur occasionally in nearly every part of Europe, but it is seldom that the whole of the continent is affected by any one storm. The fall of March 9 to 12, 1901, however, was observed practically all over Europe.[b] The area covered is given by Hellmann and Meinardus as at least 300,000 square miles of land surface and 170,000 square miles of ocean. The fall of February 22, 1903, covered an area nearly as large.[c] The amounts of dust actually brought into Europe by the various falls are difficult to determine on account of the meager data available, both as to area covered and amount of deposited dust per unit area. The latter figure is also liable to much variation from place to place. A few estimates are found in the literature and are given in Table VIII.

[a] Der grosse Staubfall, p. 30–31 (1901). Palmeri (Rend. R. Accad. sci. fis. Naples (3) 7: 155 [1901]) gives two determinations of the quantity of the fall at Naples which are not quoted by Hellmann and Meinardus. They are 9.3 and 10.3 grams per square meter. The value given by Hellmann and Meinardus for Naples is 11 grams per square meter. Palmeri's values are probably the more accurate.

[b] See authorities cited on p. 89.

[c] See authorities cited on p. 90. This fall was observed in England more widely than any other. The area affected in that country is given by Mill and Lempfert Quart. jour. Roy. meteor. soc. 30: 57 [1904]) as 20,000 square miles.

TABLE VIII.—*Total quantities of dust deposited in Europe by various falls.*

Date.	Location.	Kilograms.	Tons.
1859[a]	Westphalia	1,200,000,000	1,325,000
1863[b]	Canary Islands	5,900,000,000	6,500,000
1864[c]	Silesia	400,000,000	440,000
February, 1888[d]	Silesia and environs	12,852,000	14,147
March 9–12, 1901[e]	Europe	1,782,200,000	1,960,420
Do.[e]	North Africa (approximated)	1,500,000,000	1,650,000
Do.[e]	Total	3,282,200,000	3,610,420
February 22, 1908[f]	England	9,100,000,000	10,000,000

[a] Chauveau—Ann. Soc. météor. France **51**: 72 (1903).
[b] von Fritsch—Allgemeine Geologie, p. 212 (1888). The quantity is given as 3,944,000 cubic meters. In changing this to kilograms I have used the value given by Hellmann and Meinardus (Der grosse Staubfall, p. 31) for the average specific gravity of sirocco dust, namely, 1.5. This allows for entangled air. The true specific gravity of the dust material is about 2.5. See Macagno and Tacchini—Ann. meteor. ital. (2) **1**: 66 (1879); and Silvestri—Atti Accad. Gioenia Catania (3) **12**: 133 (1878).
[c] Cohn—Abh. Schles. Ges. vaterl. Kultur **1864**: 31–50.
[d] Camerlander—Jahrb. geol. Reichsanst. **38**: 304 (1888). This value is intended as a minimum estimate.
[e] Hellmann and Meinardus—Der grosse Staubfall, p. 31 (1901).
[f] Mill and Lempfert—Quart. jour. Roy. meteor. soc. **30**: 57 (1904). This estimate is admittedly based on insufficient data and is probably too high.

Of these, only that of Hellmann and Meinardus for the fall of March 9 to 12, 1901, can claim any degree of accuracy. It is based upon a number of observations of the amount of dust per unit area, and the calculations of areas covered, etc., were made with care. The other estimates depend upon such inadequate data that they can scarcely be considered more than guesses. In spite of this unsatisfactory nature of the estimates it is apparent that the total quantity of sirocco dust which falls in Europe is quite large. From the figures of Hellmann and Meinardus, the European area covered by the fall of March 9 to 12, 1901, is seen to be 437,500 square kilometers[a] (168,437 square miles), while the amount of this fall was 1,782,200,000 kilograms.[b] The average fall on this occasion was therefore 4,780 kilograms per square kilometer, or 4.78 grams per square meter (12.3 tons per square mile). At a specific gravity of 2.0[c] this would give 2,390 cubic centimeters of dust per square meter of surface, or a layer 0.239 mm. thick. And if a storm as violent as that of March, 1901, be assumed to occur once in five years, or if the total dust accumulation from the less violent storms during five years' time be assumed equal to that carried by the storm of March,[d] 1901, there

[a] Der grosse Staubfall, p. 31 (1901).

[b] Table VIII.

[c] The specific gravity is taken higher in this case than in Table VIII, because we are here dealing with the rate of growth of the soil by the addition of dust, and on becoming a part of the soil the dust loses much of the pore space which it possesses when freshly fallen and in a loose, unpacked condition. It is still necessary, however, to take a specific gravity lower than that of the actual material of the dust, because the soil itself is to a certain degree loose and porous; 2.0 seems a fair average value.

[d] This does not seem excessive in view of the fact that there have occurred since 1900 two storms (March, 1901, and February, 1903) each of which produced a deposit of probably about the amount given. The other less extensive storms (of which some ten or twelve are recorded in this period) would probably bring the total quantity deposited since 1900 up to two or three times the assumed value. Accurate data are lacking for the years previous to 1900, but there is no reason to think that the average deposit was greatly less than at present.

will be 0.239 mm. of dust deposited every five years, or 4.78 mm. per century, and in the three thousand odd years during which we have authentic historic evidence for the occurrence of these storms there will have been added to the soil in the regions affected 143.4 mm., or over 5½ inches, of material from the desert. This estimate will be much too low for Italy, southern France, and the Tyrol, because the storms are there more frequent than assumed, and the amount of dust deposited by each storm is greater. On the other hand, the estimate is probably too high for England and northern Germany.

It does not follow that the surface of southern Europe has actually been raised 5½ inches in the last thirty centuries, or that its soil now contains a quantity of desert dust which would, if collected, produce a layer of that thickness. The processes of soil loss and decay affect the wind-deposited material as well as that from other sources, and it, like everything else in the soil, is continually being both supplied and removed. The important point is that wind-borne material is being supplied to the soil of southern Europe at a rate which is geologically quite rapid. This conclusion is confirmed by the geologic evidence of the removal of thick strata which must once have covered the Sahara. There is no reason to believe that physiographic conditions in the Sahara have been during recent geologic time essentially different from those at present existing,[a] and the degradation of this area must therefore be ascribed almost entirely to deflation.[b] Of course, not all of the dust has been deposited in Europe. Most of it has fallen in Africa itself, in Asia Minor, and in the Mediterranean Sea and the Atlantic Ocean.

THE CONTINUAL DRIFT OF SOIL MATERIAL WITH THE WIND.

The phenomena exhibited by drifting sand and by dust storms differ only in degree from what is continually taking place everywhere in the form of the slow and unnoticed drift of soil material backward and forward by the winds.[c] It is only under exceptional circumstances that the amount of material being so transported at any one instant becomes great enough to be perceptible to the senses, but there are many evidences that much unnoticed transport does exist, and that over considerable periods of time its results exceed in importance those of the more spectacular manifestations of the same action. Dust storms are paroxysms. They form the intensive phase, the continual drift the extensive one, of the phenomena. It is the continually drifted material which forms the transient part of the dust of the atmosphere—transient because it remains in suspension only under the action of the wind and sinks more or less rapidly when the wind fails.

[a] This question is fully discussed by Walther—Wüstenbildung, Chapter I (1900).
[b] Zittel opposes this conclusion (Geol. Bau libyschen Wüste, p. 18 [1880]).
[c] Cf. Menzel—Kosmos 2: 237–239 (1905).

ACCUMULATIONS OF DUST.

The measurement of the amount of this drifting soil while it is actually in transport is almost impossible, and the evidence of the existence of the action is dependent on more or less indirect data, an important item of which is the well-known fact that dust rapidly accumulates in all places where it can remain undisturbed. This does not mean that dust reaches only protected places, but that it is only there that it can accumulate in sufficient quantity to become perceptible. Also the dust which falls on the soil is immediately incorporated therewith, and unless in some way very different from the soil material can not be distinguished from it, while dust which settles in houses, etc., at once becomes noticeable on account of its contrast with its environment. Just as much or more dust settles in the fields, but it belongs there and is unnoticed. When because of difference of color between the dust and the soil (as, for example, in the case of sirocco dust),[a] the presence of snow on the ground, or similar reasons, the field dust becomes perceptible, its amount is seen to be considerable.

The presence of dust in places where it can be seen is too familiar to need any proof. The floors of unused rooms are soon dust-covered and deposits inches deep will accumulate in time. The beams under the roofs of barns and similar partially open buildings gather thick deposits on their upper surfaces. None of these places is particularly easy of access to the dust, and probably much more dust is deposited in the open fields, where every wind has full play. It may be argued that in the open fields the dust is not deposited but kept in motion, and that deposits in houses, etc., are really made because the wind does not have full sweep and is compelled to drop its load. To a certain extent this is true, but the vegetation of the open country forms, as already explained, an entanglement which must cause the progressive deposition of much of the atmospheric load. There are, of course, places in the open fields where dust will not be dropped, or will not remain if dropped; more than this, there are places where dust is removed (for if there were not, whence would come the dust?), but there are many other places where deposit is going on much more rapidly than indoors. That the respective locations of these areas of erosion and deposition change from year to year with changes in vegetation, wind, etc.—that any particular field is being eroded this month and receiving deposits next month—does not at all weaken the conclusion that dust is probably being deposited (and removed) more rapidly in the open than in places where its presence is immediately perceptible.

[a] Another case (cement dust) is cited by Peirce—Science (n. s.) **30**: 652 (1909).

In Edinburgh, in 1902, Black[a] made some measurements of the amount of dust deposited in an open rain gauge having a funnel 6 inches in diameter, and found it to vary between 25 and 160 grains (1.62 to 10.37 grams) per month. Disregarding the values for certain months when much dust was raised by building operations nearby, the maximum value is 80 grains (5.18 grams). The average for the eight months, the values for which are believed to be trustworthy, is 42.3 grains (2.74 grams) per month, or 1.16 ounces (32.89 grams per year). This was over an area of 28.27 square inches (circle 6 inches in diameter), and amounts to 150 grams per square meter per month, or 1.8 kilograms per square meter (5,157 tons per square mile) per year. At a specific gravity of 2.0 this equals a layer about 0.04 centimeter (about 0.16 inch) thick deposited in one year. Some other determinations made at the same time and place gave, for the dust deposited in an open dish, 3.8 ounces per square foot (1,159 grams per square meter, or 3,315 tons per square mile) per year. The amount deposited in an open dish is naturally less than the deposit in a rain gauge, as the latter is much better fitted to entrap and retain the dust. Of course these figures are of no great quantitative value, as there is no assurance that the dust collected was composed of soil materials. However, Edinburgh is not a smoky city, and it is probable that at least a large part of the dust was drifting soil.[b] Black gives no data as to its composition, but he speaks of it as "sand," which would indicate that he considered it mineral in nature.

Professor Fry, in Cincinnati, has made some similar experiments on the amount of dust collected in buckets kept partly full of water and placed on the roofs of various buildings.[c] The dust was filtered off, extracted with concentrated hydrochloric acid, and weighed. The amount deposited at the various stations during July, August, and September, 1906, varied from 0.464 gram to 22.550 grams per square foot, with an average of 5.6 grams per square foot (60.28 grams per square meter) per month, or 723 grams per square meter (2,062 tons per square mile) per year. The months during which observations were made are the clearest of the year in Cincinnati, and the estimates given are probably lower than the yearly average. The material collected was carbonaceous and ashy, and appeared to be largely

[a] Quart. jour. Roy. meteor. soc. 29: 134 (1903). For a brief notice of similar measurements in 1903 (less accurate because of building operations near by), see Symons's meteor. mag. 39: 29 (1904).

[b] For data as to the composition of city dusts, etc., see p. 104.

[c] This work was done for the Smoke Abatement League, of Hamilton County, Ohio, and was reported at a meeting of the Cincinnati Section of the American Chemical Society, on October 17, 1906. A short abstract was published in the Announcement of the Section for 1907, pp. 18–19. I am indebted to Professor Fry for kindly sending me a fuller report of the work than is given in this abstract.

derived from coal smoke. No attempt was made to determine the amount of soil material which it contained.

The presence of much drifting soil in open fields has been shown by Emeis,[a] who collected the soil in a glass of water exposed on top of a low wall. He made no quantitative measurements. Alluard[b] measured the amount of blown soil (mostly volcanic dust from neighboring deposits) which collected in the cistern fed by the rain water from the roof of the observatory at Puy-de-Dôme, France. He obtained 73 grams per square meter of roof surface during two and a half months. His estimate of the yearly average was 100 grams per square meter.

The presence of snow on the ground furnishes an indicator for the dust, and the dirty appearance of snow a few days old is familiar to all. This is especially noticeable when the snow has partially melted and the dust has thereby become concentrated in the residue. The last remnants of a snowdrift are always much discolored. Observations on the presence of soil dust in snow have been made in Switzerland by Fischer;[c] in Germany by Flögel,[d] Chelius,[e] and Emeis;[f] in England by Preece[g] and Irwin;[h] and in Canada by Rae;[i] and the deposition of dust with drifting snow has even been suggested as a source of the loess.[j] During the winter of 1887–88 in central and northern Saxony so much dust was moved by the wind that layers 2, 3, and even 4 centimeters thick were found covering the snowdrifts in exposed locations.[k] On this dust layer being covered by a second snowfall the dust deposition was repeated and there was thus produced a considerable thickness of interstratified layers of dust and snow. It is possible that the strata of ice in the high latitude tundras may have originated in a similar way, having been once on the surface and covered with soil transported by wind and water.[l] In

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[a] Allg. Forst-Jagdztg. **78**: 403 (1902).

[b] Compt. rend. **100**: 1081–1083 (1885).

[c] Mitth. naturf. Ges. Bern **1867**: 210–213.

[d] Zs. Met. **16**: 324 (1881).

[e] Neues Jahrb. Min. **1892**, I: 226.

[f] Allg. Forst- Jagdztg. **78**: 403–414 (1902). See also von Lasaulx—Encyclop. der Naturw., Abt. II **1**: 74 (1882); and note in Nature **27**: 496 (1883).

[g] Nature **23**: 336–337 (1881).

[h] Jour. Soc. chem. ind. **21**: 533 (1902).

[i] Nature **33**: 244–245 (1886).

[j] Davison—Quart. jour. Geol. soc. **50**: 472–487 (1894). This article contains much information on the collection of dust in snowdrifts. On the movement of dust with the great snow storms of the steppes, see Nehring—Tundren und Steppen, pp. 44–45 (1890).

[k] Sauer and Siegert—Zs. deut. geol. Ges. **40**: 575–582 (1888).

[l] See Leffingwell—Jour. geol. **16**: 56–63 (1908). For alternative explanations see Tyrrell—Jour. geol. **12**: 232–236 (1904); and Stefánsson—Bull. Amer. geog. soc. **42**: 337–345 (1910).

January, 1901, there was blown onto the ice-covered surface of Lake Müritz (northwest of Berlin) a sheet of dust from 0.1 to 0.2 millimeter thick and extending about 5 kilometers from the east bank.[a] The total quantity deposited was estimated as at least 5,000 cubic meters. If such quantities of dust are collected in so short a time, and if enough dust to be easily perceptible is gathered everywhere by a comparatively transient snow covering, it is apparent that the aggregate amount of blown dust must be very large, and especially is this conclusion inevitable when it is remembered that these indications are all observed during the season when most of the soil surface is frozen or ice covered and thereby protected from wind action. It seems probable that much larger quantities of dust are moved during the summer, though the absence of any indicator such as the snow prevents its presence being noticed.

Even in regions of perpetual snow in the arctics and on high mountains, dust is found in and on the snow and ice,[b] and N. A. E. Nordenskiöld[c] found on the ice of Greenland a deposit which he thought to be a new mineral species, and named cryokonite. He supposed it to be of extraterrestrial origin. It has since been shown by Holst[d] and von Lasaulx[e] that this material is a mixture of ordinary minerals,[f] and has undoubtedly been derived from the

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[a] Peltz—Archiv Ver. Naturg. Mecklenburg **55**: 180 (1901).

[b] On the occurrence of mineral dust in arctic snow and ice see W. E. Parry—Journal of a third voyage for the discovery of a Northwest Passage, pp. 23, 104, 155 (1826); McClure—The discovery of the Northwest Passage by H. M. S. "*Investigator*," 2d ed. (Osborn), pp. 193, 229 (1857); M'Clintock—The voyage of the "*Fox*" in Arctic seas, p. 146 (1859); Koldewey—The German Arctic expedition of 1869–70, English ed. of 1874, p. 120; Flight—Geol. mag. n. s. **2**: 157–159 (1875); Nares—Narrative of a voyage to the Polar sea, vol. **1**, pp. 149, 168–169, vol. **2**, pp. 12, 59, 61 (1878); Jensen—Peterm. Mitth. **26**: 103 (1880); Carstensen—Globus **47**: 154 (1885); Greely—Three years of Arctic service, vol. **1**, pp. 312, 398–399, vol. **2**, pp. 30–31 (1886); Kindle—Amer. jour. sci. (4) **28**: 175–179 (1909). Terrestrial dust has similarly been observed in the snow on the Himalaya Mountains (altitudes up to 14,700 feet). See Arthur Schuster—Rept. Brit. assoc. **1883**: 126–127; Tanner—Proc. Roy. Geog. Soc. (n. s.) **13**: 411 (1891); and Oldham—Quart. jour. Geol. soc. **50**: 486 (1894).

[c] Öfvers. K. Vet.-akad. förh. **31**: 3–12 (1874); Voyage of the *Vega*, vol. **1**, pp. 327–331 (1881).

[d] Sveriges geol. undersökning ser. C, No. **81**, 1886.

[e] Tschermak's min. Mitt. (n. s.) **8**: 519–526 (1880). On cryokonite see also Wülfing—Neues Jahrb. Min. Beilagebd. **7**: 152–174 (1890).

[f] Quartz, mica, orthoclase, plagioclase, magnetite, garnet, epidote, hornblende, etc., mainly quartz. The chemical composition of an air-dried sample was as follows:

SiO_2	62.25	Na_2O	4.01
Al_2O_3	14.93	P_2O_5	.11
Fe_2O_3	.74	Cl	.06
FeO	4.64	Hygroscopic water	.34
MnO	.07	Loss on ignition	2.86
CaO	5.09		100.12
MgO	3.00		
K_2O	2.02		

Analysis by Lindström, quoted by von Lasaulx, loc. cit. See also Nordenskiöld—Met. Zs. **11**: 215 (1894), where this and other analyses (also by Lindström) are quoted

rocks of the coast and other exposed places, and blown by the wind to the surface of the ice fields.

It may be argued that the house dust, etc., is not soil material, but organic remains, soot, ashes, rust, etc. However, all examinations of blown dust have shown the presence therein of the ordinary soil minerals in addition to various matters of animal, vegetable, and industrial origin. For instance, dust collected from the roof of the National Museum at Melbourne, Australia, was largely mineral and contained quartz, augite, tourmaline, olivine, zircon, feldspar (orthoclase, albite, labradorite, etc.), epidote, magnetite, limonite, zoisite, and calcite.[a] Dust deposited on the frozen surface of one of the lakes at Madison, Wis., by the dust storm of February, 1896, was examined by Prof. W. H. Hobbs and found to be composed of the ordinary minerals of granitic rocks.[b] Dust collected from the snow north of Kiel, Germany, contained quartz, feldspars, mica, hornblende, and clayey substances.[c] Dust from the top of the tower of the cathedral at Nancy contained quartz, feldspars, micas, pyroxene, tourmaline, rutile, enstatite, peridot, zircon, corundum, hematite, calcite, and clay.[d] Similar dusts deposited by Australian[e] and Russian[f] dust storms, collected from snow at Madrid,[g] at the top of Ben Nevis, Scotland,[h] at Trondhjem, Norway,[i] in eastern Sweden,[j] etc., possess a like composition.[k] It is true that in cities, and especially near manufacturing centers, much dust is discharged into the air by various industrial enterprises,[l] and the dust of cities is likely to contain a smaller percentage of soil material than dust collected in less crowded regions. Nevertheless, the dust of New York City was found to contain much quartz and numerous fragments of other minerals,[m] and dust collected in Berlin was found to be largely mineral.[n]

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[a] Chapman and Grayson—Vict. nat. **20**: 30 (1903).

[b] Observation published only in the daily press. For the information given and for a sample of the dust I am indebted to Prof. J. A. Jeffery, now of the Michigan Agricultural College, who collected the dust.

[c] von Lasaulx—Tschermak's min. Mitt. (n. s.) **3**: 529 (1880).

[d] Thoulet—Compt. rend. **146**: 1347 (1908), **150**: 947–949 (1910).

[e] L. Hart—Austr. photog. rev. **1897**: 9; Chapman and Grayson—loc. cit.; Liversidge—Jour. Proc. Roy. soc. N. S. Wales **36**: 242 et seq. (1902).

[f] Klossovskĭ—Bull. Soc. belge. géol. **8**, Proc. verb.: 239–240 (1895).

[g] Macpherson—Nature **29**: 224 (1884). Cf. also ibid., p. 174.

[h] Murray and Renard—Nature **29**: 590 (1884).

[i] Reusch—Nature **27**: 496 (1883).

[j] Hildebrandson, quoted by N. A. E. Nordenskiöld—Geol. mag. (2) **3**: 295 (1876). See also Nordenskiöld—Geol. fören. förh. **14**: 377 (1892), **15**: 417–459 (1893).

[k] For examination of various dusts and soots see Hartley and Ramage—Proc. Roy. soc. **68**: 97–109 (1901). Cf. also Flögel—Zs. Met. **16**: 324 (1881).

[l] See Leymann—Die Verunreinigung der Luft durch gewerbliche Betriebe, Handb. der Hygiene, Suppl. bd. **3**, pp. 27–126 (1903).

[m] Egleston—Trans. Amer. soc. civ. eng. **15**: 656 (1886).

[n] Himmel und Erde **18**: 279–282 (1906).

So largely is ordinary dust made up of soil material that its color and other properties are determined by the nature of the prevailing soil, or at least of that part of the soil which is fine enough to be moved by the wind. The "alkali" dust of the western United States is white, the dust of laterite regions is reddish,[a] etc.

The dust which accumulates where it can be recognized as wind-borne is usually removed, naturally or artificially, practically as fast as it gathers; and accumulations on the soil itself can not be recognized as differing from local soil materials. Sometimes, however, eolian dusts can be identified, as, for instance, the fine white powder found by Gilbert[b] in cavities in the cindery lava of the Lake Bonneville district, or the black or reddish clayey dust found by Foureau in sheltered rock cavities in the northern Sahara.[c] The writer has found similar dust (or rather very fine sand) in cavities in the tufa of Rattlesnake Butte, near Fallon, Nev. The natives of central Australia find sand in birds' nests in trees high above the ground.[d] It is said that the bark of trees growing east of the Columbia River in southeast Washington is so full of blown sand as to dull saws used to cut them. Raulin,[e] in 1845, found on the tops of the high mountains of Crete pockets of soil which he believed to have been deposited by the wind. Similar occurrences have been observed on Mount Monadnock, in New Hampshire.[f] Reid[g] cites several instances of wind-deposited material on chalk cliffs and sand hills in England. A. D. Hall[h] mentions the growth of soil on shingle recently won from the sea; and Kinahan[i] describes a similar deposit on a surface of bog-iron ore—wind action being responsible in both cases. There is always a possibility (though usually a slight one) that these deposits may have been derived from the decay of the rock (rain wash is excluded by the location), but this can not be the case with the pockets of soil frequently found on tops of buildings.[j] Dirt tends to collect in low spots on the roof, and especially to be washed into rain spouts, necessitating occasional cleaning. It can have gotten there only by wind-drift from the

[a] See Walther—Einleitung in der Geologie als historische Wissenschaft, p. 810 (1894).

[b] Lake Bonneville, U. S. geol. surv. Monogr. 1: 325 (1890).

[c] Documents scientifiques mission saharienne, vol. 1, p. 234 (1904). For a similar observation in the Salton Basin, see Tolman—Jour. geol. 17: 156 (1909).

[d] J. W. Gregory—Dead heart of Australia, p. 233 (1906).

[e] Bull. Soc. géol. France (2) 15: 139 (1857). Cf. the observations of Virlet d'Aoust and of Stur, cited on p. 140 below.

[f] Unpublished observation of Mr. W. O. Robinson, of this bureau. For further notice of this soil, see p. 162.

[g] Geol. mag. (3) 1: 166, 168 (1884).

[h] The soil, p. 10 (1903).

[i] Geol. Mag. 6: 267 (1869).

[j] Reid—Geol. mag. (3) 1: 167 (1884); Richthofen, in Neumayer—Anleit. wiss. Beob. auf Reisen, 2d ed., vol. 1, p. 254 (1888).

ground below, and that it contains the soil minerals is shown by the not infrequent occurrence in it of growing plants, sprung from seeds likewise blown in by the wind or carried by birds.

The deposition of blown soils on a large scale is discussed below under the head of eolian geologic formations.

ADMIXTURE OF LOCAL MATERIAL IN DUST FALLS.

Additional evidence of the constant presence of soil material in the atmosphere is found in the fact that nearly every fall of volcanic ash, sirocco dust, etc., which has been examined has been found to contain material of local origin.[a] Only the dust collected on shipboard is free from contamination of this sort.[b] This constant local admixture has been observed in atmospheric dusts in general by von Lasaulx[c] and Black;[d] in sirocco dust by Cohn,[e] Max. Schuster,[f] von John,[g] Klein,[h] Becke,[i] Früh,[j] Mill and Lempfert,[k] Krebs,[l] Prinz,[m] Macagno and Tacchini,[n] and others; in Australian blown dust by Steel;[o] in Krakatoa ashes by Judd,[p] etc. The amount of local material is frequently great enough to change the properties of the fallen dust and prevent its accurate analysis.[q] It has been suggested by Klein[r] that the local mineral matter in air dusts may have an industrial origin, being derived from impurities in the coal burned in furnaces, but it seems more likely that much of it, at least, is derived from the soil itself.

NATURAL BURIAL OF ARTICLES IN THE SOIL.

It is well known that stones and similar articles left lying on the ground gradually disappear beneath the surface, and that the soil

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[a] Of course, when the fall is too heavy the presence of local material is obscured.

[b] See Herrmann—Annalen Hydrog. **31**: 478–479 (1903).

[c] Tschermak's min. Mitt. (n. s.) **3**: 530 (1880).

[d] Quart. jour. Roy. meteor. soc. **29**: 134 (1903).

[e] Abh. Schles. Ges. vaterl. Kultur **1864**: 31–50.

[f] Sitzungsb. Kaiserl. Akad. Wiss. Vienna **93**: 105–116 (1886).

[g] Verh. geol. Reichsanst. **1896**: 259.

[h] Sitzungsb. K. Preuss. Akad. Wiss. Berlin **1901**: 612 et seq.

[i] Anz. Kaiserl. Akad. Wiss. Vienna **38**: 107–109 (1901).

[j] Met. Zs. **20**: 175 (1903).

[k] Quart. jour. Roy. meteor. soc. **30**: 76 et seq. (1904).

[l] Globus **84**: 184 (1903).

[m] Ciel et terre **24**: 25, 75, 81 (1903).

[n] Ann. meteor. ital. (2) **1**: 70 (1879).

[o] Rept. Austr. assoc. adv. sci. **7**: 334–335 (1898). See also Liversidge—Jour. Proc. Roy. soc. New South Wales **36**: 258 et seq. (1902).

[p] Roy. soc. Rept. on Krakatoa, p. 41 (1888).

[q] Cf. p. 94 above, and see also Mill and Lempfert—loc. cit., in note *k* above. Sirocco dust is sometimes greatly changed in color by local admixture. See Hellmann and Meinardus—Der grosse Staubfall, p. 90 (1901), and Ditte—Ciel et terre **25**: 502 (1904).

[r] Sitzungsb. K. Preuss. Akad. Wiss. Berlin **1901**: 612 et seq.

similarly tends to "creep up" about walls, fences, etc. Even more striking is the fact that a layer of ashes, lime, etc., if spread on a field will gradually sink *as a layer*, and may be found years later as a distinct stratum a few inches below the surface. Many examples of these phenomena are cited by Darwin.[a] The relics of ancient civilizations, as, for instance, arrowheads in America, coins and medals in Europe, etc., are always found beneath the surface. It is extremely unlikely that all of these objects were originally buried by man, and it is therefore necessary to ascribe their present position to the action of some natural agency which causes the covering of objects left on the surface,[b] and which acts with considerable rapidity, only a few years being required for burial to be effected. The débris left on the battlefields of the civil war has already entirely disappeared, and that it has actually "sunk" and not been artificially removed is proven by the frequency with which swords, belt buckles, and other articles are unearthed by cultivators of fields which were once the scene of battles.

This process of natural burial was ascribed by Darwin[c] to the action of earthworms, and by Kinahan[d] to the accumulation of the products of vegetable decay. It is probably in part due to rain wash and in part to the deposit of blown dust,[e] and perhaps in part also to the mutual movements of the soil particles, as described on page 16.[f] This last factor can never be more than a minor one, but the determination of the relative importance of the others is very difficult. There is no doubt that each is of predominant importance in certain cases, and that all are of some effect in all cases. As a generally predominant factor, the accumulation of vegetable remains, as suggested by Kinahan, may be at once rejected, since the material which is found to cover the buried articles is largely mineral, being simply ordinary soil. The importance of rain wash can usually be determined from the topography of the country, and there are many cases

[a] Formation of vegetable mould, chap. 3 (1881). See also Kinahan—Geol. mag. **6**: 109–115, 263–268, 348–351 (1869); Key—Nature **17**: 28 (1877); Dancer—Proc. Phil. soc. Manchester **16**: 247 (1877); and Urquhart—Nature **27**: 91 (1882).

[b] Of course there are places where the erosive agencies of wind and water are so active that bodies do not sink below the surface because the surface soil itself is too rapidly removed. On such areas stones do not tend to disappear, but to appear (from below), and of all crops that of the stones is the largest. The stony hillside fields of New England belong to this class. Similarly, in arid regions there is formed a "desert pavement," as already described.

[c] Proc. Geol. soc. London **2**: 574–576 (1838); Trans. Geol. soc. London (2) **5**: 505–509 (1840); Formation of vegetable mould, 1881.

[d] Geol. mag. **6**: 263–268, 348–351 (1869).

[e] For suggestions to this effect, see Rafinesque—Amer. Jour. Sci. **1**: 397–400 (1819); Proctor—Pleasant ways in science, p. 379 (1878); Richthofen—Verh. geol. Reichsanst. **1878**: 296; and Hughes—Nature **30**: 57 (1884).

[f] For instance, see Scott—Nature **78**: 376 (1908).

where the situation of the field excludes this factor at once. Also rain wash would not in general produce deposits of uniform thickness, as seen in the burial of layers of foreign material, as described above, or in the case noted by Kinahan,[a] where the uprights of a long iron railing were buried to a uniform depth by the up-creep of soil.

It is more difficult to discriminate between the effects of earthworm action and of the deposition of blown dust. Each would probably produce a deposit of reasonably uniform thickness and each deposit would probably consist of particles of about the same size. A grain too large to be swallowed by the worm would also be too large to be moved by the wind, and where numerous larger grains are found in the surface deposit[b] their presence is probably to be ascribed to water action. It is possible that a careful mineralogical examination of the deposit might furnish criteria, at least in some cases. If it were found to be composed entirely of the material of the subsoil, it might reasonably be referred to worm action. If, on the other hand, much foreign material were found to be present, it would be reasonable proof of the activity of the wind.

It seems at any rate not improbable that the share of the wind in the formation of "vegetable mould" is far greater than that assigned to it by Darwin.[c] Burial by earthworms is in great part a real sinking of the object due to removal of soil from beneath, and it is difficult to see how pavements or layers of foreign material could sink in this manner without more distortion of level than is observed,[d] and particularly difficult to imagine a stone wall thus sinking without losing its perpendicular position.[e] It would seem that in these cases either wind or rain has been the main agent. The same is true in general of the burial of ancient buildings in England and elsewhere.[f] Whether in general in the open fields more material is deposited by the winds or by the worms, it is impossible to say. Neither can be neglected as an active agent.

THE IMPORTANCE OF SOIL DRIFT.

It is apparent from the above that the quantities of soil drifted back and forth by the wind are considerable, though perhaps not

[a] Geol. mag. **6**: 266 (1869).

[b] For an instance, see Darwin—The formation of vegetable mould, N.Y., 1898, p. 225.

[c] The formation of vegetable mould, N. Y., 1898, note on p. 237.

[d] Various instances of the discovery of ancient floors, etc., the original level surface of which was still maintained, are cited by Darwin (The formation of vegetable mould, N. Y., 1898, chaps. 3 and 4).

[e] An instance is given by Darwin—loc. cit., p. 227.

[f] See Darwin (loc. cit., chap. 4) for many instances. In most of these cases rain has no doubt been very active. J. E. Lee, however (in his trans. of Keller—Lake dwellings in Switzerland, footnote on p. 367 [1866]), cites a case where rain action was impossible and where nevertheless Roman remains were found in England 5 to 6 feet below the surface. A case of the burial of ruins by blown volcanic dust on top of Puy-de-Dôme, France, is cited by Alluard—Compt. rend. **100**: 1082 (1885).

susceptible to accurate measurement. In spite of the small amounts of soil which can actually be seen to blow about, it is not difficult, when the persistence of the action is considered, to believe that the aggregate amount is very great. One of Darwin's greatest contributions to scientific thought was his insistance—in connection with evolutionary doctrines, the study of coral islands, and elsewhere—that effects of great magnitude may be produced as the cumulative result of very small but frequent secular changes.

As already mentioned, no marked deposits are likely to be produced by soil drift. It is true that certain areas, as indicated in the last section, are receiving deposits, but this material is derived from other areas where the protection furnished by vegetation or other means is less adequate to prevent attack. In fact, the protection is nowhere sufficient absolutely to prevent attack, and soil drift is always back and forth, with a tendency for the best protected areas to lose less than they gain. The sinking of objects into the soil does not always require the deposit of any great amount of foreign matter. If the surface soil is continually being shifted by the wind, bodies which are too heavy to be thus moved will sink through the rest, and stones, etc., may thus be lowered in absolute position as well as covered by extraneous material.[a] This of course can not take place with the pavements, buildings, etc., mentioned above, and if these are covered by wind action it must be by virtue of actual deposit on top of them. The material so gained must naturally be made up by material lost from some other area.

To the agriculturist the main importance of this back-and-forth drift lies in its efficacy in increasing and maintaining the heterogeneity of the soil. The instances of its occurrence given above are merely those in which the action chances to be visible on account of some special and unusual condition, and there can be no doubt that most of the soil drift is not observed and not observable. The surface of every field probably receives material from every field in the neighborhood and from many at a distance, though how much material is thus received it is impossible to say. It is seldom sufficient to modify greatly the appearance and general properties of the soil. Sandy soils remain sandy and clayey ones clayey in spite of wind drift. It is worth noting, however, that unless either the soil or the added material were very exceptionally distinctive, 4 or 5 per cent of blown dust could be present without being detectable by any known methods of soil examination. The blowing in of distant material is at least a possible source of supply of minerals in which a particular soil is naturally deficient, and these minerals do not need to be present in any large amount to be ample for the needs of the soil.[b]

[a] For an example in the dunes of Sylt, Germany, see Meyn—Abh. geol. Sp.-Karte Preuss. 1: 652, 666 (1876).

[b] See Bull. 30, Bur. of Soils, U. S. Dept. Agr. (1905).

TRUE ATMOSPHERIC DUST.

The constant presence of fine dust in the atmosphere is evidenced by the floating motes which are seen in a beam of light through a dark room. The dust is of various materials—organic remains, smoke thrown off by fires and by various industrial operations, mineral matter from the soil, etc., together with small amounts of material of volcanic and cosmic origin. By far the larger part is transient and its discussion belongs to the last chapter, under the head of soil drift, though the transient part is, of course, not entirely made up of soil material. Much of the industrial and domestic débris remains in suspension only a short time and does not travel far from its place of origin. There is, however, in the air some dust which is deposited only with extreme slowness and which forms the more or less permanent part of the atmospheric load. It must not be understood that particles of this material never settle out of the atmosphere; they do, and are constantly being replaced by new ones. The permanence of atmospheric dust is a permanence of dust content rather than of individual particles. Atmospheric dust can perhaps be roughly defined as the solid material which is normally present in the atmosphere in distinction to that which belongs to the ground surface and is only abnormally atmospheric. No sharp or rigid distinctions or definitions are possible or desirable.

THE PHYSICS OF DUST SUSPENSION.

It is not necessary to revert to hypotheses of mutual electrical repulsion [a] or similar phenomena in order to explain the fact that dust particles (and also drops of water) remain suspended in the air for an indefinite period. The simple resistance of the air to the movement of such very minute bodies is amply sufficient to reduce their rate of fall to the requisite degree. Particles of volcanic ash, organic matter, etc., fall especially slowly because of their irregular shape, but even perfect spheres are easily supported if small enough. Flögel [b] has calculated that a sphere of iron 0.018 mm. in diameter would fall at a maximum rate of 1.69 meters per second. The metallic spheres actually found in atmospheric dust (see p. 120) are almost always smaller than this,[c] and would consequently sink with a

[a] As advocated by Rowell (Rept. Brit. Assoc. **1840**: 47; Nature **29**: 251 [1884]), and by Preece (Nature **29**: 180 [1883]).

[b] Zs. Met. **16**: 326 (1881). See also Plumandon—Poussières atmosphériques, p. 33 (1897).

[c] Tissandier found them to vary from 0.01 to 0.001 mm. in diameter (Compt. rend. **78**: 823 [1874], **80**: 59 [1875]). See also Tacchini—Mem. Soc. spettrosc. ital. **8** Append.: 19–20 (1879); Ditte—Ciel et terre **25**: 498 (1904). Tissandier's work on atmospheric dusts was published in the Compt. rend. **78**: 821–824 (1874), **80**: 58–61 (1875), **81**: 576–579 (1875), **83**: 75–78, 1184–1186 (1876), and **86**: 450–453 (1878). A more general article was published in the Rev. sci. (2) **18**: 814–820 (1880). His earlier observations were collected and amplified in a work entitled Les Poussières de l'air, published in 1877.

maximum velocity even lower than that assumed. The continual eddying of the air currents as described on page 34 is therefore well able to keep them in suspension.

The vitreous and mineral fragments are even more easily suspended,[a] and the organic particles more easily still. Air dusts sometimes contain particles of soot, volcanic glass, etc., as large as 0.1 mm. in their longest diameter.[b] The consequent movements of the air currents carry this dust far and wide and mix it so thoroughly that all local differences disappear, and the true atmospheric dust becomes practically the same the world over.

Of the atmospheric dust which is carried to the ground a small part doubtless falls of itself during periods of calm,[c] and a large part is filtered out of the lower air by vegetation,[d] but by far the largest part is washed out by rain and snow. Not only is dust entangled by falling water drops and snow crystals, but the dust particles themselves act as nuclei around which the rain drops condense.[e]

It is possible that the dust itself, through the modifications which it brings about in the heat-absorbing power of the air of which it is a part, tends to set up currents which help keep it in suspension.[f] The dust particles doubtless absorb radiant heat more rapidly than does the surrounding air, and hence when dusty air is exposed to the sun's rays each dust mote will act as a miniature furnace. The aggregate result is that dusty air becomes more highly heated by the

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[a] On the flotation of volcanic dust, see Murray and Renard—Proc. Roy. soc. Edinburgh **12**: 486 (1883–4).

[b] Tissandier—Compt. rend. **78**: 823 (1874), **81**: 577 (1875); Les Poussiéres de l'air, pp. 9–10. See also Table III, p. 45, above.

[c] For instance, the air of the desert is always clearer in the morning. See Hedin—Scientific Results, vol. **1**, p. 212 (1904); and Huntington—Pulse of Asia, p. 185 (1907). A similar greater clearness of the morning air in humid regions would be noticed were there so great a difference in the rapidity of air movement in the daytime and at night as there is in the desert.

[d] See Rolleston—Jour. Roy. geog. soc. **49**: 346–347 (1879) and authorities there cited.

[e] See Aitken's papers in the Trans. and Proc. Roy. soc. Edinburgh, 1880 to 1902 (cited in the bibliography). His work is largely summarized in a paper before the International Meteorological Congress held at Chicago in 1893: Bull. **11**, Weather Bureau, U. S. Dept. Agr., pp. 734–754. See also Coulier—Jour. pharm. chim. (4) **22**: 165–173 (1875). Condensation can, however, take place on nuclei other than dust particles (ions, etc.), though not so readily. See Barus—Pub. Carnegie Institution of Washington, **40**, 1906; **62**, 1907; **96**, 1908. Also several articles by him in Science, 1904–1908, and a short article in Nature **69**: 103 (1903). For a short general discussion of condensation nuclei, see C. T. R. Wilson—Nature **68**: 548–550 (1903). Melander has observed in the dust from Vesuvius certain particles which seem more than normally efficient in condensing moisture on themselves (Öfvers. Finska vet. soc. förh. **43**: 148–160 [1901]). He believes these to be particles of more or less deliquescent salts.

[f] This was suggested for sirocco dust by Mill and Lempfert—Quart. jour. Roy. meteor. soc. **30**: 71 (1904). On heat absorption, etc., by dust in air, see Serrell—Nature **30**: 53–54 (1884).

sun than air carrying little or no suspended matter. Therefore if a dusty stratum lie below an empty one, the lower may become sufficiently heated to rise through the higher. It is quite possible that this action is important in thoroughly mixing suspended dust through the air. Aitken[a] has made the interesting observation that dust motes are not affected by solar heat focused by a large lens, where larger objects would be burnt up at once. This is probably because the mote loses heat so rapidly to the surrounding air.

THE SOURCES OF ATMOSPHERIC DUST.

In the atmosphere generally most of the dust is probably organic, and consists of animal and vegetable fragments, living bacteria and spores, grains of pollen, fragments of diatoms, etc. The predominance of organic matter is due to the low specific gravity and irregular form of these fragments, which consequently possess a high surface-mass ratio and are easily suspended. Mineral grains are heavier and more nearly spherical, and therefore tend to settle out more rapidly. True soil material is, however, never entirely absent from atmospheric dust.

In the air of cities and other places where many fires are burning the air is much contaminated by soot and fine ash discharged by the chimneys. Much of this material is so fine that it falls very slowly and forms part of the permanently suspended dust of the atmosphere. Great fires, especially forest and prairie fires, make a similar contribution. Much dust other than smoke can also be traced to human activity—as, for instance, organic fibers from the making and handling of textiles, dust originating from street traffic, etc.[b]

Another source of atmospheric dust is the spray blown inland from the seas, from which is derived the sodium chloride known to be present in some quantity in rain,[c] the amount decreasing with distance from the seashore. Du Bois[d] gives yearly averages varying from 0.66 to 30 milligrams per liter of rain. He calculates the annual amount of sodium chloride deposited on the dunes of Holland to be at least 6,000,000 kilograms (13,227,720 pounds). The mean pro-

[a] Trans. Roy. soc. Edinburgh **42**: 489 (1902).

[b] An interesting illustration of the odd materials which can be found in atmospheric dust is furnished by Flögel's detection in dust from snow of ultramarine crystals, probably derived from blued clothes (Zs. Met. **16**: 368 [1881]).

[c] See Schübler—Grundsätze der Meteorologie, p. 140 (1831); Barral—Proc.-verb. Soc. Philom. **1852**: 29–30; Compt. rend. **35**: 427–431 (1852); Arago—Oeuvres complétes, vol. **12**: p. 391–407 (1859); Passerini—Boll. Soc. meteor. ital. (2) **13**: 66 (1893); also Ciel et terre **10**: 438 (1890), **12**: 94–96 (1891), and **15**: 570 (1895); and especially Du Bois—Ciel et terre **28**: 233–245 (1907), Arch. Mus. Teyler (2) **10**: 461–467 (1907). Cf. the observation of Curtis of salt incrustation on an instrument exposed to an ocean gale, but situated 1 mile inland (Quart. jour. Roy. meteor. soc. **30**: 89 [1904]).

[d] Ciel et terre, loc. cit.

portion of sodium chloride in rain in England is 2.2 milligrams per liter.[a] At Rothamsted it is 2.01 milligrams per liter,[b] at Nantes, France, it is 14 milligrams per liter,[c] and at Troy, N. Y., 2.7 milligrams per liter.[d] The amounts contained in rain during heavy on-coast storms are much greater. Lobry de Bruyn[e] observed 350–500 milligrams per liter in Holland and the British Rivers Pollution Committee[f] found 218 milligrams per liter at Lands End, England. Clyde[g] states that the rain on the shores of the Caspian is sometimes salt to the taste, which statement is discredited by Petzholdt,[h] but receives support from the observation of J. W. Gregory[i] that in central Australia the first drops of a rain storm are salty. The amounts of salt in rain in the interior of the continents are of course much less, but are still considerable at some distance from the coast[j] and even on high mountains.[k] It has been suggested that the continental salt deposits have been formed from wind-borne oceanic salt,[l] and also that blown dust is the source of the chlorine in the cerargyite ores of arid regions.[m]

A rain of solid salt crystals, doubtless derived from the evaporation in the air of drops of spray, occurred at Mantua, Italy, July 25, 1878, and has been reported by Agostini.[n] Sodium chloride has also

[a] 6th Rept. Gt. Brit. Rivers Pollution Com., p. 425 (1874). See also the analyses by Robert Angus Smith on pp. 18–19 and 27–32 of the report cited, and on pp. 281–380 of his work "Air and Rain" (1872).

[b] Warington—Jour. Chem. soc. London **51**: 502 (1887). The annual rainfall at Rothamsted is 31.65 inches, so that the yearly deposit of sodium chloride is 24 pounds per acre.

[c] Bobierre—Compt. rend. **58**: 755 (1864).

[d] Mason—Water supply, p. 205 (1896).

[e] Quoted by Du Bois—Ciel et terre **28**: 233–245 (1907).

[f] Loc. cit., p. 29.

[g] School geography, p. 32 (1870).

[h] Nature **29**: 172 (1883).

[i] Dead heart of Australia, p. 137 (1906). Korty (Electricity **10**: 93 [1896]) describes a salt storm in eastern Utah so severe that the deposited salt interfered with the working of the telegraph.

[j] See figures for Rothamsted, England, and for Troy, N. Y., given above.

[k] Müntz—Compt. rend. **112**: 447–450 (1891).

[l] Pošepny—Sitzungsb. Kaiserl. Akad. Wiss. Vienna **76**: 179–212 (1877), Verh. geol. Reichsanst. **1877**: 222–223; Walther—Wüstenbildung, p. 145 (1900); Ackroyd—Proc. Yorkshire geol. and polyt. soc. (n. s.) **14**: 401–421 (1901), Geol. mag. (4) **8**: 445–449 (1901), Quart. statement Palestine explor. fund **1904**: 64–66; Pivovarov—Pédologie **1906**: 67–80. For the contrary opinion, see Tietze—Jahrb. geol. Reichsanst. **27**: 341–374 (1877); Joly—Geol. mag. (4) **8**: 344–350 (1901). The very thorough and careful investigations of Holland and Christie (Rec. Geol. surv. India **38**: 154–186 [1909]) on the salt deposits of Rajputana led to the conclusion that the salts of these deposits are in the main wind-borne from the marine salt-flats of the Rann of Cutch.

[m] Beck—Lehre von den Erzlagerstätten, 3d ed., vol. 2, p. 324 (1909); Keyes—Econ. geol. **2**: 778–780 (1907), Trans. Amer. inst. mining engs. **39**: 166–169 (1908).

[n] Ann. meteor. ital. (2) **1**: 3–8 (1879). See also H. O. Dwight, London Times correspondence, Dec. 25, 1883, and the rain of salt crystals mentioned on p. 91 above. Another case, at Pocatello, Idaho, was reported in the daily press on June 21, 1894.

been detected in the air itself when no rain was falling. Determinations by Duphil[a] gave, for seashore air, from 0.3 to 15 milligrams per cubic meter and for forest air from 0 to 6 milligrams per cubic meter. In England, Smith[b] found an average of 0.40 milligrams per cubic meter, with extremes of 0.07 and 1.15. Sirocco dust collected on a ship off the African coast in February, 1898, contained over 25 per cent of sea salt.[c]

Some of the atmospheric dust is of volcanic origin, and it is probable that a small part is extraterrestrial. These materials will be discussed below.

THE QUANTITY OF ATMOSPHERIC DUST.

The collection and examination of atmospheric dust is a matter of peculiar difficulty If the air be passed through water,[d] as, for instance, in a gas-absorption bulb, the dust is completely collected but its properties are often changed by the contact with water, and it is difficult to remove the water without further modifying the nature of the dust. The method of collecting dust on plates smeared with vaseline or glycerine[e] is open to similar objections. Filters of cotton-wool stop most of the dust, but it can not afterwards be separated from the material of the filter. Gun-cotton may be used instead of ordinary cotton, and then dissolved in ether,[f] but this will mean the loss of the ether-soluble constituents of the dust itself. The very fine platinum screen of A. Schuster[g] would either let some of the dust through or would clog so rapidly as to be useless. The method of Rubner[h] by comparing the discoloration of paper disks through which samples of air have been filtered gives good results for soot content but permits no examination of the amount or character of the mineral dust which may be present. Boxes, through which dust-laden air is allowed to blow, or funnels built on the rain-

[a] Soc. sci. et stat. zool. d'Arcachon, Trav. des Lab. **5**: 58–59 (1900–1).

[b] Air and Rain, pp. 427–429 (1872).

[c] Dinklage—Annalen Hydrog. **26**: 253–254 (1898).

[d] Tissandier—Les poussières de l'air, p. ix, 2 (1877).

[e] Airy—Nature **9**: 439–440 (1874); Ranyard—Mon. notes Roy. astron. soc. **39**: 165 (1879); Miquel—Ann. Obs. Montsouris **1879**: 448–456; J. B. Cohen—Jour. Soc. chem. ind. **16**: 411–412 (1897); Duphil—Soc. scient. et stat. zool. d'Arcachon, Trav. des Lab. **5**: 62 (1900–1); Glibert—Zs. Gewerbehyg. **15**: 257 (1908).

[f] See Ditte—Ciel et terre **25**: 498 (1904). Winslow's method (Eng. news **60**: 748 [1908]), using a filter of granulated sugar afterward dissolved in water, is still less accurate.

[g] Rept. Brit. assoc. **1884**: 38.

[h] Hygien. Runds. **10**: 257–263 (1900), Arch. Hygiene **57**: 365 (1906). See also Orsi—Ibid. **68**: 10–21 (1908); Liefmann—Deut. Vierteljahrs. Öffent. Gesundheitspflege **40**: 325–344 (1908); Friese—Sitzungsb. Isis Dresden **1909**: 8.

gauge principle and arranged to face the wind,[a] collect the dust in excellent condition, but do not collect it all. The finest materials are blown clear through and escape. In fact the material collected is more largely the transient air dust (drifting soil) than true atmospheric dust. There has not yet been devised an apparatus which will collect all the dust of the air, or even a representative sample of it, in a dry and unmodified condition.

Tissandier measured the dust in Parisian air by collecting it in water and obtained values of from 6 to 23 milligrams per cubic meter.[b] There are two errors in this method, one due to the volatility in steam of certain organic constitutents of the air dust, and the other to the solubility in water of the material of the various containing vessels. The two errors being, however, in opposite directions, tend to neutralize each other.

The number of dust particles (with no regard to size or weight)in a given amount of air may be determined with fair accuracy by condensing moisture on the particles and counting the water drops produced. Aitken's dust-counter is based on this principle.[c] Vörner[d] claims that the dust in the air may be measured by allowing the particles to settle on a surface of black polished wood, where they will stick and may be counted. Relative measurements of the amount of dust in the air may also be made by observing its transparency.[e] The transparency, however, depends on the humidity as well as the dust content.[f]

The amount of dust in the atmosphere is of course exceedingly variable from time to time and from place to place. Sometimes the air is so full of dust that dry fogs, "dark days," etc., result, while at other times it is nearly dustless. The number of dust particles is highest in deserts and near thickly settled regions and when the wind blows therefrom. It is least in winds coming from large oceans or over unsettled regions (vegetation-covered, of course). There is less dust in the air over the Highlands of Scotland than in any other

[a] Himmel und Erde **18**: 279 (1906). Cf. the observation of Curtis on dust collected on the sheet of a sunshine recorder (Symons's meteor. mag. **38**: 210–211 [1903]).

[b] Compt. rend. **78**: 822 (1874), and Les Poussières de l'air, p. 2 (1877).

[c] See his papers cited in note [e], p. 111; also Barus—Bull. **12**, Weather Bureau, U. S. Dept. of Agr. (1895), and references there cited. The Aitken counter counts only the dry particles in the air. Those with moisture already condensed on them do not show (Melander—Sur la condensation de la vapeur d'eau dans l'atmosphère, p. 118, 1897). On the use of the Aitken counter see also articles given in the bibliography under Barus, Conrad, Ficker and Defant, and Rankin.

[d] Prometheus **16**: 173 (1904).

[e] See Aitken's papers; also Jahresb. Sonnblick-Vereines Vienna **10**: 31–32 (1902) and references cited on pp. 117–119 below.

[f] Aitken—loc. citati.

inhabited region so far examined.[a] The dust content of the upper air is somewhat less than that of the lower.[b]

All the above concerns the dust actually suspended in the air. The quantity of true atmospheric dust which is deposited on the surface is even more difficult to measure, because of the impossibility of distinguishing between it and the transiently suspended drifting soil. The amount of the former which is spontaneously deposited on a free surface is probably very slight indeed, for, as before stated, nearly all such material which falls comes down with rain or snow. As an indication, however, of the amount of material of all kinds which is deposited from still air, it is interesting to note certain measurements by Tissandier of the quantity of dust collected on a flat surface exposed to the atmosphere. Near Paris he obtained in one night 1.5 to 3.5 milligrams per square meter in spite of some loss in collecting.[c] Later he obtained, this time in the country, 10 to 50 milligrams per square meter in 24 hours.[d] With improved apparatus at the Observatory of Sainte-Marie-du-Mont, he obtained 2.1, 4.0, 8.1, 9.2, and 12.1 milligrams per square meter per twenty-four hours.[e] Much larger amounts would doubtless be deposited on a vegetation-covered surface, or where the wind movement (what little existed) was otherwise checked. Neither does this include the dust carried down by rain.

Tissandier has made some determinations of the amount of solid matter in rain water, obtaining values of from 25 to 172 milligrams per liter.[f] Similar values for snow water are from 16 to 75 milligrams per liter.[g] A. Schuster[h] found over 100 milligrams of dust in 25 cubic feet of snow from the Himalaya Mountains. As the amounts of rain and snow which fell in the various cases are not given, the figures are of little value. The first drops of a rain storm will of course contain the largest percentage of dust, and as the storm continues the air is gradually washed clean.

THE OPTICAL EFFECTS OF DUST IN THE AIR.

The fine particles of air dust, by selectively scattering the light they receive and thus diffusing the blue while allowing the rest of the spectrum to pass, are responsible for the blue color of the

[a] Aitken—Trans. Roy. soc. Edinburgh **42**: 486 (1902).

[b] Fridlander—Quart. jour. Roy. meteor. soc. **22**: 184–203 (1896). See also Lüdeling—Illust. aeron. Mitt. **7**: 321–329 (1903).

[c] Compt. rend. **78**: 823 (1874).

[d] Ibid. **81**: 576 (1875).

[e] Les Poussières de l'air, p. 8 (1877).

[f] Les Poussières de l'air, p. 16.

[g] Tissandier—Compt. rend. **80**: 59 (1875), **81**: 576 (1875).

[h] Rept. Brit. assoc. **1883**: 126.

sky[a] and the red color of sunlight which has passed through more than the usual thickness of air, or through air containing an unusual quantity of dust. Thus the sun is always redder at sunset or sunrise, and the sky assumes by reflection various tints of red or orange. When the air is abnormally dusty, as in deserts or after volcanic eruptions, the sunsets are especially brilliant.[b] Indeed, it frequently happens that the air is dusty enough to cause the sun to appear red even during the middle of the day, and the green and blue colors occasionally observed[c] are probably also caused by dust, though in a manner not perfectly understood. Atmospheric dust is also the cause of the partial polarization of light from the sky,[d] and of the very rare dust halos or diffraction coronæ about the sun and moon.[e]

From a practical standpoint, however, the most important of the optical effects of dust in the air is the decrease of atmospheric transparency which it causes. An unusually large quantity of dust in the air will produce a dry fog or haze, and this will happen whenever meteorological conditions are such as to cause the accumulation in the lower strata of the dust constantly supplied to the atmosphere, or whenever an extraordinarily large quantity of dust is rapidly supplied by fires, volcanic eruptions, etc. The autumn atmosphere in temperate regions is always more or less hazy, because conditions are then such that dust from the soil, plants, etc., tends to accumulate in the lower air.[f] In equatorial Africa the dust from the ground hangs in the air at certain seasons,

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[a] On the theory of selective scattering and its effects see Tyndall—Phil. mag. (4) **37**: 384–394 (1869), **38**: 156–158 (1869); Rayleigh—ibid. (4) **41**: 107–120, 274–279, 447–454 (1871), (5) **12**: 81–101 (1881), **47**: 375–384 (1899); E. L. Nichols—Phys. rev. **26**: 497–511 (1908); Pernter—Meteorologische Optik, pp. 560–654 (1910). A bibliography and summary of the literature on the cause of the blue sky and on the polarization of daylight is given by N. E. Dorsey—Mon. weath. rev. **28**: 382–389 (1900).

[b] Kiessling—Sitzungsb. Ges. ges. Naturw. Marburg **1904**: 9–11. The appearances after the great eruption of Krakatoa in August, 1883, were very remarkable and long continued. They are fully described by F. A. R. Russell—Roy. soc. Rept. on Krakatoa, pp. 151–199 (1888). Similar phenomena were observed after the eruptions in the West Indies in 1902. See Nature **66**: 79, 101–102, 199, 222–223, 294–296, 370, 390 (1902); Gruner—Mitth. naturf. Ges. Bern **1903**: 1–5; and others.

[c] For several instances of blue and green sun see Archibald—Roy. soc. Rept. on Krakatoa, pp. 199–217 (1888); and Russell—ibid., pp. 384–405.

[d] See N. E. Dorsey—Mon. weath. rev. **28**: 382–389 (1900), where the literature is cited and reviewed.

[e] A dust corona was well developed after the Krakatoa eruption and was named Bishop's Ring after S. E. Bishop, of Honolulu, who made the first detailed observations of it. See Archibald—Roy. soc. Rept. on Krakatoa, pp. 232–262 (1888). A similar ring was observed after the eruptions of 1902. See Forel—Compt. rend. **137**: 380–382 (1903), **138**: 688–690 (1904), **140**: 694–696 (1905); H. H. Clayton—Science (n. s.) **17**: 150–152 (1903). For the theory see Pernter—Meteorologische Optik, Absch. III, pp. 469–470 (1906).

[f] W. L. Moore—Mon. weath. rev. **29**: 374 (1901).

producing a thick haze; the "callina" or hot-weather haze of Spain is due to similar causes;[a] and dry fogs and hazy conditions are common in all desert and steppe regions.[b] Those accompanying dust storms and dust falls have been mentioned already. The storms of the spring of 1893 in southeastern Russia gave rise to a fog which reached to Sweden and Denmark.[c]

Much haze and dry fog is also caused by smoke from large fires, such as burning forests or the prairie fires which were formerly common on the Great Plains. The burnings of the peat moors of East Friesland have produced similar phenomena in Germany.[d] Smoke haze frequently travels great distances; thus in 1857 moor smoke was observed at Vienna and at Krakau, over 500 miles away.[e] In cities smoke from industrial and domestic fires plays a large part in decreasing the transparency of the air—so large that the smoke nuisance is a great and continually growing evil.[f] W. N. Shaw[g] estimates that the smoke refuse of London is over 300 tons per day.

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[a] Schmid—Lehrbuch der Meteorologie, pp. 793–794 (1860).

[b] Hornemann—Voyage dans l'Afrique Septentrionale, vol. 1, p. 111 (1803); Khanykov—Soc. géog. Paris, Rec. voy. mém. 7: 448–451 (1864); Henderson and Hume—Lahore to Yárkand, pp. 65, 107, 133 (1873); Stoliczka—Verh. geol. Reichsanst. 1874: 120; Richthofen—China, vol. 1, p. 97 (1877); Tietze—Jahrb. geol. Reichsanst. 27: 347–348 (1877); Durand—Compt. rend. Assoc. franç. avan. sci. 7: 474–477 (1878); Hellmann—Monatsb. K. preuss. Akad. Wiss. Berlin 1878: 397; Nachtigal—Sahárâ und Sûdân, vol. 2, p. 130 (1881); Przhevalskĭĭ—Reisen in der Mongolie, p. 3 (1881); Rohlfs—Kufra, p. 156 (1881); Hanusz—Bull. Soc. hong. géog. 15: 419–434 (1887); Brewer—Bull. Amer. geog. Soc. 21: 212 (1889); Walther—Einleitung in der Geologie als historische Wissenschaft, p. 595 (1894); Blake—Quart. jour. Geol. soc. 53: 228 (1897); Hedin—Through Asia, vol. 1, pp. 450, 516, 523, 545, 597 (1899), Central Asia and Tibet, vol. 1, pp. 266–267, 272, 278, 287 (1903); Fischer—Peterm. Mitt. Ergänzungsh. 133: 122 (1900), Zs. Ges. Erdk. Berlin 35: 411–412 (1900), Mitt. geog. Ges. Hamburg 18: 154–156 (1902); Russell—U. S. Geol. surv. Bull. 199: 18 (1902); Ann. Soc. météor. Paris 53: 25–26 (1905); Stein—Sand buried ruins of Khotan, pp. 237–238, 243, 244 (1903); J. W. Gregory—Dead Heart of Australia, pp. 65–67, 79 (1906); Takagi—Kisho Sh. 25: 219–232 (1906); Huntington—Pulse of Asia, pp. 92, 103, 134–135, 157 (1907); Hornaday—Campfires on desert and lava, pp. 170–172 (1908); Bowman—Bull. Amer. geog. soc. 41: 150 (1909). The desert of Kirman in Persia is an exception to the general rule (Henderson and Hume, loc. cit.).

[c] Klossovskĭĭ—Ciel et terre 15: 562 (1895). On the common dust fog ("mgla") in southern Russia, see the works given in the bibliography under Agrinskĭĭ, Bondyrev, Braunov, Heintz, Ia. I., Ivanov, Morozov, N–v., Nikolaev, Polferov, S–n., Safonov, Sanin, and Schultz.

[d] Fincke—Der Moorrauch in Westphalen, 1825; Arends—Abhandlungen von Rassenbrennen und den Moorbrennen, 1826; Veltmann—Arch. ges. Naturl. 10: 266–272 (1827); Woyna—Zs. Forstwiss. 35: 116–119 (1903).

[e] Prestel—Peterm. Mitth. 4: 106–110 (1858).

[f] See the bibliography of Frazer—Trans. Amer. inst. min. eng. 38: 520–555 (1908); also Tschorn—Die Rauch-Plage, Handb. der Hygiene, Suppl.-Bd. 3: 127–200 (1903); Rubner—Archiv. Hyg. 59: 131–149 (1906); Cohen and Ruston—Nature 81: 468–469 (1909).

[g] Jour. San. inst. 23: 318 (1902).

Dry fogs have frequently followed violent volcanic phenomena, and have been observed at great distances from the seat of disturbance. Thick dry fog was observed in Germany after the eruption of Kötlugia (Iceland) in 1721,[a] and both in Germany and the rest of Europe after the eruption of 1755.[b] The great dry fog of 1783, which covered all Europe and persisted for months, causing all kinds of unusual meteorological phenomena, is believed to have been due to the dust ejected during the violent eruption of Skaptar Jökull, in Iceland, in May and June.[c] Hazy conditions, beautiful sunsets, etc., also followed the eruption of Tomboro in 1815;[d] of Vatna Jökull in 1875;[e] of Krakatoa in 1883;[f] of Pelée in 1902,[g] and of Vesuvius in 1906.[h] The Krakatoa haze was remarkable for the unusually great altitude at which it was observed.

The thermal intensity of the sun's rays may be greatly diminished by passage through dusty air, even when no haze is visible, as was shown by the behavior after the eruptions of Pelée and La Soufrière of the electrical sunshine recorder at St. Kitts (West Indies), the mercury in which barely touched the contact wires even on the clearest days, although normally in that latitude it extends well into the upper bulb.[i] Hedin[j] has made analogous observations of the decrease of insolation and nocturnal radiation during dusty weather in the Takla-makan desert.

Arctic travelers have described a haze due to floating ice-crystals and quite similar in appearance to the typical dust haze.[k]

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[a] Kaemtz—Meteorology, Walker's transl., p. 470 (1844).

[b] Saccheti—Phil. trans. **49**, I: 409–411 (1755); Whytt—Phil. trans. **49**, II: 509–511 (1756).

[c] Brugman—Verhandelingen over een zwavelagtigen Nevel, 1783; Bertholon—Lit. mag. and Brit. rev. **2**: 97–103 (1789); Ann. chim. phys. (2) **13**: 106 (1820); Martins—Proc. verb. Soc. philom. Paris **1851**: 5–11; Ditte—Ciel et terre **25**: 533 (1904); and the literature cited by F. A. R. Russell—Roy. soc. Rept. on Krakatoa, pp. 388–392 (1888).

[d] Howard—The climate of London, vol. **2**, pp. 267–281 (1833).

[e] F. A. R. Russell—Roy. soc. Rept. on Krakatoa, p. 401 (1888).

[f] See references cited on p. 117.

[g] See references cited on p. 117; also Gockel—Met. Zs. **20**: 328 (1903); Lŭboslavskiĭ—Meteor. Vĕst. **1903**: 243–248; H. E. Hobbs et al.—Mon. weath. rev. **30**: 487–488 (1902).

[h] Meunier—Compt. rend. **142**: 938 (1906).

[i] H. E. Hobbs—Mon. weath. rev. **30**: 488 (1902). See also Dufour—Met. Zs. **20**: 223 (1903); Gorczynski—Compt. rend. **138**: 255–258 (1904); Abbe—Astron. Nachr. **165**: 285–288 (1904); Kimball—Proc. conv. U. S. Weather Bur. officers **3**: 69–77. (1904), Mon. weath. rev. **33**: 100–101 (1905). It has been suggested by P. and F. Sarasin that the glacial period was caused by decrease of insolation due to an abnormal amount of dust in the air (Verh. naturf. Ges. Basel **13**: 603–618 [1902]).

[j] Through Asia, vol. **1**, p. 466 (1899).

[k] Belcher—The Last of the Arctic Voyages, vol. **1**, pp. 318, 358 (1855); I. I. Hayes—The open Polar sea, p. 194 (1867); Payer—New lands within the Arctic Circle, vol. **2**, pp. 50, 61 (1876); De Long—The voyage of the *Jeannette*, vol. **1**, pp. 147–148 (1883); etc.

EXTRATERRESTRIAL DUST.

Though most of the dust of the atmosphere is undoubtedly of terrestrial origin, there is evidence that some small quantity of cosmic material is present. The meteoric masses encountered by the earth probably aggregate not less than 100 tons per day,[a] and only a few of these reach the surface. The remainder are disintegrated in the atmosphere, and the product of their disintegration must be largely fine dust, of which that from stony meteorites would differ so slightly from ordinary terrestrial material as to be difficult if not impossible of identification. The material of metallic meteorites is more characteristic, and it is probable that from the disintegration of these bodies arises at least a part of the magnetic particles found in air dusts.[b] Especially is this origin probable for all or a part of the minute spheres of metallic iron which are often present. These were first found by Ehrenberg[c] in dust which fell on the ship *Josiah Bates* south of Java, January 24 to 25, 1859, and have been carefully studied by N. A. E. Nordenskiöld[d] in dusts collected from snow and ice in high latitudes and by Tissandier[e] in dusts from many different sources. They are not always perfect spheres, but often more or less irregular in shape, with rounded edges, and greatly resemble particles rubbed from the surface of metallic meteorites.[f] They usually contain nickel and cobalt[g] as do meteoric irons in general. They have been found in dust directly collected from the air by Phipson,[h] Marié-Davy,[i] and Tissandier;[j] in dust from the top of a church tower by Thoulet;[k] in dust from snow by Yung,[l] Flögel,[m] A. Schuster,[n] and N. A. E. Nordenskiöld;[j] in sirocco dust

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[a] Smyth—Nature **29**: 150 (1883); Langley, New York Tribune, Jan. 2, 1884.

[b] For notices of several cases in which a fall of fine dust accompanied the fall of a meteor, see N. A. E. Nordenskiöld—Met. Zs. **11**: 212 (1894).

[c] Monatsb. K. Preuss. Akad. Wiss. Berlin **1858**: 1–41. See also Reichenbach—Ann. Phys. Chem. (Poggendorf) **106**: 476–490 (1859).

[d] Compt. rend. **77**: 463–465 (1873), **78**: 236–239 (1874).

[e] Compt. rend. **80**: 58–61 (1875), **81**: 576–579 (1875), **83**: 75–78 (1876). These observations are collected and supplemented in Les Poussières de l'air. See also Ditte—Ciel et Terre **25**: 497–510, 525–534 (1904).

[f] Tissandier—Compt. rend. **83**: 76–78 (1876).

[g] Tissandier—Compt. rend. **83**: 75–76 (1876); and Les Poussières de l'air, p. 49.

[h] Meteors, aerolites and falling stars, pp. 229–230 (1867); Compt. rend. **83**: 364–365 (1876).

[i] Bull. mens. Obs. Montsouris **5**: 11 (1876).

[j] Loci citati.

[k] Compt. rend. **146**: 1347 (1908).

[l] Bull. Soc. vaud. sci. nat. **14**: 493–506 (1877); and Compt. rend. **83**: 242–243 (1876).

[m] Zs. Met. **16**: 321–330 (1881).

[n] Rept. Brit. assoc. **1883**: 126.

by Macagno and Tacchini,[a] Palmeri,[b] Silvestri,[c] and Roster.[d] Ferruginous nuclei in hail have been observed by Eversman,[e] von Baumhauer,[f] and others. These spherules can be detected in most atmospheric dusts, but are comparatively few in number, and occasionally altogether absent. Camerlander[g] found none in the dusts examined by him, and von Lasaulx[h] found none in cryokonite. Palmeri[i] found magnetic iron oxide, but no spherules, in several samples of sirocco dust from Naples. Liversidge[j] found no spherules in the air-borne dust of New South Wales, but did find that it contained traces of cobalt, nickel, and metallic iron. Spherules could not be found in the sirocco dust which fell in Europe, April 21, 1880,[k] or that which fell October 14, 1885.[l] They have been found in Sahara sand by Tacchini[m] and by A. Schuster;[n] in various rocks by Andrews,[o] Hoffmann,[p] and Meunier and Tissandier;[q] and are nearly always present in deep-sea deposits.[r] Similar iron spherules, but containing no nickel, have been found by Tissandier[s] in the mud of the Seine.

It is not improbable that some of the supposedly cosmic spherules may be derived from iron furnaces, fires, etc. Spherules quite similar to the atmospheric ones, but somewhat larger, have been obtained by Rose[t] (working with Ehrenberg) by burning iron in oxygen, and by Tissandier[u] by burning iron wire in air; and bodies of the same general nature have been found by Meunier and Tissandier[v]

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[a] Ann. meteor. ital. (2) **1**: 69 (1879); see also Tacchini—Mem. Soc. spettrosc. ital. **8** Append.: 19–20 (1879).

[b] Rend. R. Accad. Sci. fis. Naples **18**: 112–113 (1879).

[c] Trans. R. Accad. Lincei (3) **4**: 163–166 (1880).

[d] l'Orosi **8**: 75 (1885).

[e] Ann. Physik **76**: 340 (1824).

[f] Compt. rend. **74**: 679 (1872).

[g] Jahrb. geol. Reichsanst. **38**: 281–310 (1888).

[h] Tschermak's min. Mitt. (n. s.) **3**: 524 (1880).

[i] Rend. R. Accad. Sci. fis. Naples (3) **7**: 156–157, 163, 172 (1901).

[j] Jour. Proc. Roy. soc. N. S. Wales **36**: 243–244, 254–255 (1902).

[k] Daubrée—Compt. rend. **90**: 1098–1101 (1880).

[l] Max. Schuster—Sitzungsb. Kaiserl. Akad. Wiss. Vienna **93**: 85 (1886).

[m] Trans. R. Accad. Lincei (3) **7**: 135 (1883).

[n] Rept. Brit. assoc. **1882**: 91.

[o] Rept. Brit. assoc. **1852**, II: 34–35.

[p] Trans. Roy. soc. Canada **8**, III: 39–42 (1890).

[q] Compt. rend. **86**: 452–453 (1878).

[r] Murray—Proc. Roy. soc. Edinburgh **9**: 247–262 (1876); Meunier and Tissandier—Compt. rend. **86**: 451 (1878); Murray and Renard—Proc. Roy. soc. Edinburgh **12**: 490–494 (1883–84).

[s] Compt. rend. **83**: 78 (1876).

[t] Reichenbach—Ann. Phys. Chem. (Poggendorf) (4) **16**: 479 (1859).

[u] Compt. rend. **81**: 578 (1875).

[v] Compt. rend. **86**: 451 (1878).

at the bottom of a well in which dynamite had been exploded in an iron casing. Ditte's[a] argument that a cosmic origin in all cases is proven by the content of nickel and cobalt is unsound in the light of the discovery by Hartley and Ramage[b] of these elements in ordinary coal smoke. On the other hand, the occurrence of spherules in ancient rocks laid down long before the advent of man, or at least of man's industrial operations,[c] speaks strongly for a cosmic origin. Taken together the evidence seems to favor the conclusion of an origin in some cases cosmic and in some terrestrial. A partial terrestrial origin seems especially probable in the light of the observation of Yung[d] that more iron is found in the atmosphere at lower than at higher altitudes.

GEOLOGIC FORMATIONS OF EOLIAN ORIGIN.

In deserts eolian sands and dusts form a large part of the recent deposits, but in ordinary climates the wind-borne detritus is usually so incorporated with material from other sources that it can not be distinguished therefrom. While it is probable that some eolian material is present in nearly all surface deposits the world over, formations which are predominantly and characteristically eolian are much less numerous and extensive than are those which are characteristically aqueous. The loess, however (as will be later discussed), is of quite wide distribution and has probably been formed, at least in part, by the wind. There are other less extensive formations which are even more exclusively eolian; as, for instance, the drifting sands already discussed at length, the volcanic ash deposits which will be discussed later, and especially the eolian soils.

EOLIAN SOILS.

In a few places, mainly in or near areas of more or less complete aridity, the soil has been identified as largely of direct eolian origin. Thus on the Snake River Plains in Idaho the lava is thinly covered with a very fine yellowish sand, which is evidently wind deposited and which has probably been brought by the wind from a distance, though it may have originated in some part by disintegration of the lava.[e] Similarly the only soil on the lava plains of the Alamogordo

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[a] Ciel et terre **25**: 525–527 (1904).

[b] Proc. Roy. soc. **68**: 97–109 (1901); Hartley—Proc. Roy. Dublin Soc. (n. s.) **9**: 547–555 (1901). The latter article discusses the industrial origin of atmospheric dusts in general.

[c] See page 121; also Tissandier—Rev. sci. (2) **18**: 817 (1880).

[d] Tissandier—Poussières de l'air, p. 37 (1877).

[e] Russell—U. S. Geol. surv. Bull. **199**: 21, 25, 68, 73, 101, 107, and especially 136–139 (1902). From a personal examination of these soils the present writer has come to entire concurrence in Russell's conclusions. The conditions in the valleys just to the west of the Snake River Plains are quite similar. See Russell—U. S. Geol. surv. Bull. **217**: 19 (1903).

Desert in New Mexico has been brought there by the wind.[a] Areas of soil formed or modified by wind action have been found in many of the areas surveyed by this bureau,[b] and the present writer has examined other areas in Maryland, Idaho, Oregon, Nevada, and California. Stevenson, Schaub, and Snyder[c] believe that the "Missouri loess" of southwestern Iowa is wind formed, and Cross[d] advances a similar hypothesis in explanation of the origin of the red soil which tops the gravels of southwestern Colorado. In the latter case the material is supposed to have been brought by the wind from the deserts to the west. Fischer[e] believes that the "tirs" or black earth of Morocco is eolian. The eolian soils of the Mexican Plateau are noted by R. T.

[a] Macbride—Science (n. s.) **21**: 93 (1905).

[b] Following are the areas, with references to the Reports of the Field Operations of the Bureau of Soils: Merrimack County, N. H. (**1906**: 60–61); Rhode Island (**1904**: 65); Long Island, N. Y. (**1903**: 116); Niagara County, N. Y. (**1906**: 106, 107, 109); Salem, N. J. (**1901**: 136); Dover, Del. (**1903**: 150); Worcester, Md. (**1903**: 174); Easton, Md. (**1907**: 139); Norfolk, Va. (**1903**: 237); Parkersburg, W. Va. (**1908**, Advance sheets, Parkersburg Area, p. 32); Craven, N. C. (**1903**: 257); New Hanover, N. C. (**1906**: 257–268); Chowan County, N. C. (**1906**: 230); Robeson County, N. C. (**1908**, Advance sheets, Robeson Area, pp. 25–26); Charleston, S. C. (**1904**: 213); Meigs County, Ohio (**1906**: 725); Posey County, Ind. (**1902**: 451); Marshall County, Ind. (**1904**: 699); Tippecanoe County, Ind. (**1904**: 797); Newton County, Ind. (**1905**: 761, 767, 768, 769); Green County, Ind. (**1906**: 765); Saginaw, Mich. (**1904**: 612); Cass County, Mich. (**1906**: 748); Tazewell County, Ill. (**1902**: 470, 471, 473); Sangamon County, Ill. (**1903**: 715); Winnebago County, Ill. (**1903**: 768, 769); O'Fallon, Missouri-Illinois (**1904**: 837); Dubuque, Iowa (**1902**: 588); Storey County, Iowa (**1903**: 841); Tama County, Iowa (**1904**: 782–783); Henry County, Ala. (**1908**, Advance sheets, Henry County Area, p. 24); Biloxi, Miss. (**1904**: 363); Jasper County, Miss. (**1907**: 544); Superior, Wisconsin-Minnesota (**1904**: 760); Blue Earth County, Minn. (**1906**: 843, 844); Crookston, Minn. (**1906**: 884); Ransom County, N. Dak. (**1906**: 979); Carrington, N. Dak. (**1905**: 935, 936); Grand Island, Nebr. (**1903**: 939); Stanton, Nebr. (**1903**: 954); Sarpy County, Nebr. (**1905**: 901); North Platte, Nebr. (**1907**: 823–824, 830); Riley County, Kans. (**1906**: 938); Wichita, Kans. (**1902**: 635, 636); Garden City, Kans. (**1904**: 904); Lower Arkansas Valley, Colo. (**1902**: 740, 741, 753); Oklahoma County, Okla. (**1906**: 571, 572, 579); Conway County, Ark. (**1907**: 770); Vernon, Tex. (**1902**: 372); San Antonio, Tex. (**1904**: 456); Houston County, Tex. (**1905**: 543); Waco, Tex. (**1905**: 579); Henderson, Tex. (**1906**: 469); Wilson County, Tex. (**1907**: 652); Blackfoot, Idaho (**1903**: 1035); Minidoka, Idaho (**1907**: 915–916, 917, 918, 919, 921); Salt Lake Valley, Utah (**1899**: 101); Provo, Utah (**1903**: 1127, 1128–1129); Pecos Valley, N. Mex. (**1899**: 62–63); Solomonsville, Ariz. (**1903**: 1054, 1059); Salt River Valley, Ariz. (**1900**: 204, 299–302); Yuma, Ariz. (**1902**: 781–782; **1904**: 1029); San Luis Valley, Cal. (**1903**: 1104); Ventura County, Cal. (**1901**: 528); San Bernardino Valley, Cal. (**1904**: 1140–1141); Los Angeles, Cal. (**1903**: 1270–1271, 1272); Santa Ana, Cal. (**1900**: 390); Porto Rico (**1902**: 805).

[c] Iowa Agr. expt. stat. Bull. **95**: 14 (1908).

[d] Bull. Geol. soc. Amer. **19**: 53–62 (1908).

[e] Peterm. Mitt. Ergänzungsh. **133**: 117–124 (1900), Zs. Ges. Erdk. Berlin **35**: 412 (1900), Mitt. geog. Ges. Hamburg **18**: 149–159 (1902). For a contrary opinion see Gentil—Compt. rend. **146**: 243–246 (1908).

Hill,[a] and those of the steppes of southeastern Russia have been described by Pallas,[b] Bïeletskïĭ,[c] and Sibirzev.[d] The last author[e] notes similar occurrences in Central Africa. Of course, eolian loess is simply an eolian soil deposited in past ages, and those areas where loess is now being deposited by the wind are naturally areas of eolian soil. Some such are described on pages 139–140 below.

The eolian soils are in general distinguished by no special characteristic except unusual uniformity in the size of particle. Owing to the nature of air transportation (as already discussed) the particles of any one deposit are likely to be nearly of the same size, though different deposits may of course differ greatly from each other in this respect. For all other characters, including indeed the actual size of particle which prevails, an eolian soil is dependent upon the special conditions which accompanied its formation. Its mineral composition is likely, however, to be more than usually diverse because of the great extension of its agent of formation. The identification of a wind-formed soil depends both upon its general geologic and geographic situation and upon its internal characteristics, but much more upon the former than the latter. The problem differs in no way from that of the identification of soil origins in general.

Besides the areas of exclusively (or predominantly) eolian soil as just mentioned, there are many cases where the addition of some quantity of wind-blown material to a soil of other origin noticeably modifies the nature of the latter, beneficially or the reverse. Thus the writer has observed a case (at Guadaloupe, Cal.) where the addition of sand blown out of a coastal dune complex has materially improved the physical texture of the water-laid soils farther inland. Similar cases have been noted by Hughes[f] and Beadnell[g] in Egypt, and by Juritz[h] in South Africa. Haworth[i] notes the reverse condition where the addition of blown clay decreases the permeability of the soil.

THE LOESS.

The loess was first described in the valley of the Rhine, but has since been found to be very extensively developed in China, in North America, and in southeastern Europe. It consists of a yellow, or

[a] Eng. min. jour. **83**: 663 (1907). Cf. also the articles of Virlet d'Aoust and Meunier, cited on p. 140 below.

[b] Reise durch verschiedene Provinzen russischen Reiche, vol. 1, p. 365 (1771).

[c] Mater. izuch. russk. pochv **9**: 1–40 (1895).

[d] Compt. rend. Cong. géol. intern. **7**: 90–92 (1897). See also Nehring—Tundren und Steppen, pp. 126–128 (1890), and the discussion of recent loess on p. 140 below.

[e] Loc. cit. See also Walther—Einleitung in der Geologie als historische Wissenschaft, p. 811 (1894).

[f] Yearb. Khediv. agr. soc. **1906**: 133–134.

[g] An Egyptian oasis, pp. 78–79, 81 (1909).

[h] Rept. South African assoc. adv. sci. **1908**: 87–104.

[i] U. S. Geol. surv. Water supp. pap. **6**: 13 (1897).

yellowish-brown, calcareous silt-loam, remarkably uniform in mechanical composition and usually without stratification. Its component grains are angular and loosely arranged, giving it a high porosity and great absorptive power. It tends to split in vertical planes, producing perpendicular cliffs or bluffs along water courses and in other places where it is subject to erosion. Throughout many deposits of loess are fantastically formed concretions of calcium carbonate; the *Loess-Männchen* of the Germans.[a] In China, and to a less extent in other localities, these concretions are likely to occur in horizontal planes, thus simulating strata and, in connection with the vertical cleavage, causing the loess to erode in a series of terraces, the tops of which are formed (and protected) by a layer of concretions. The concretions are believed to be of secondary origin and their occurrence in horizontal planes is probably due to the percolation of water along these planes.[b] The fossils of the loess are everywhere almost entirely terrestrial in character.[c] Fresh-water

[a] Jentzsch—Zs. ges. Naturw. **40**: 82–89 (1872); Richthofen—China, vol. **1**, pp. 58–59 (1877); Frantzen—Jahrb. preuss. geol. Landesanst. **1885**: 257–266; Počta—Sitzungsb. K. böhm. Ges. Wiss. **1887**: 598–601; Jenny—Mitt. naturf. Ges. Bern **1889**: 126–127; Steinmann—Mitt. bad. geol. Landesanst. **2**: 130–133 (1893); Zahálka—Verh. geol. Reichsanst. **1896**: 285–286; Früh—Vierteljahrsch. naturf. Ges. Zurich **44**: 167 (1899). An analysis of concretions from the German loess gave:

SiO_2	34.824	$MgCO_3$	1.890
Al_2O_3, Fe_2O_3	4.204	K_2O	1.048
		Na_2O	1.202
CaO	.203	P_2O_5	.157
$CaCO_3$	55.294	SO_3	.090
MgO	.178	H_2O	.377

Blanck—Landw. Vers. Stat. **65**: 471–476 (1907). The concretions of the American loess have been described by Call—Amer. nat. **16**: 373 (1882). On the similar concretions of the loess-like deposits of the South American pampas see Ameghino—La Formación Pampeana, pp. 179–200 (1881).

[b] Richthofen—China, vol. **1**, pp. 61–62 (1877).

[c] On the fossils of the European loess see Braun—Ber. Versamml. deut. Naturf. **20**: 142–152 (1842), Neues Jahrb. Min. **1847**: 49–53; Stizenberger—Übersicht Versteinerungen Grossherzogthums Baden, pp. 30–31, 107–110 (1851); Mousson—Vierteljs. naturf. Ges. Zurich **1**: 250–259 (1856); Peters—Verh. geol. Reichsanst. **1863**: 118–120; Sandberger—Land- und Susswasserconchylien der Vorwelt, pp. 866–906 (1870–75); Jentzsch—Sitzungsb. Isis Dresden **1871**: 148–150, Zs. ges. Naturw. **40**: 96–98 (1872); Braun—ibid., p. 45; Richthofen—loc. cit.; Sandberger—Verh. med.-phys. Ges. Würzburg **14**: 125–140 (1880); Nehring—Zs. deut. geol. Ges. **32**: 468–509 (1880); Hilber—Jahrb. geol. Reichsanst. **32**: 316 (1882); Tietze—ibid., pp. 112–114; Nehring—Geol. mag. (2) **10**: 51–58 (1883); Schumacher—Erl. geol. Karte Strassburg, pp. 37–38, 41 (1883); Sandberger—Neues Jahrb. Min. **1883**: 182–183; Chelius—Notizbl. Ver. Erdk. Darmstadt **1884**: 18–19; Wahnschaffe—Jahrb. K. preuss. geol. Landesanst. **1886**: 253–258; Rzehak—Verh. naturf. Ver. Brünn **26**, Abh.: 74–78 (1887); Makowsky—ibid., pp. 205–243 (1887); Wollemann—Verh. naturh. Ver. preuss. Rheinl. Westf. **44**: 260–268 (1887), **45**: 237–291 (1888); Kafka—Sitzungsb. K. böhm. Ges. Wiss. **1889**: 195–207; Jenny—Mitt. naturf. Ges. Bern **1889**: 120–153; Sauer—Neues Jahrb. Min. **1890**, II: 93–94; Sandberger—Verh. naturf. Ges. Basel **8**: 796–801 (1890); Chelius—Notizbl. Ver. Erdk. Darmstadt **1892**: 21–23; Koch—Jahresb. Ver. Naturw. Braunschweig **1893–5**: 35–37; Nehring—ibid, pp. 45–47;

forms are rare and marine forms entirely absent. The shells of land snails and similar mollusks are especially abundant. Throughout many loessial deposits are numerous minute tubes running more or less vertically and usually lined with calcium carbonate. These tubes have been supposed to have much to do with the tendency to split in vertical planes, and have been regarded by the advocates of the theory of eolian origin as casts of the roots of plants which grew on the loess as it was being deposited. It has, however, been recently suggested by Willis [a] that the vertical cleavage is due to the peculiar physical structure developed by the settling and consolidation of the originally loose material. The horizontal interspaces between particles tend to close, whereas the vertical spaces remain of their original size, and cementing waters then tend to fill up first the smaller horizontal spaces. The resulting structure would naturally possess a roughly vertical cleavage. It is possible that the tubules may have been produced, as a phase of the same process, by the union of superposed vertical interspaces into more or less vertical tubes, which would act as passages for lime-bearing waters, become lined with calcium carbonate and take on an approximately cylindrical form.

The loess is most extensive in China, where it covers about 300,000 square miles. It has been studied and described in that country

Gutzwiller—Der Löss, pp. 14–21 (1894), Verh. naturf. Ges. Basel **10**: 634–669, 679–682 (1895); Makowsky—Compt. rend. Cong. géol. intern. **7**: 183–186 (1897); Piperoff—Beitr. geol. Karte Schweiz n. s. **37**, VII: 56 (1897); Viglino and Capeder—Boll. Soc. geol. ital. **17**: 84 (1898); Fruh—Vierteljs. naturf. Ges. Zurich **44**: 170–171 (1899); Wüst—Zs. Naturw. **71**: 442–446 (1899); Handmann—Verh. geol. Reichsanst. **1903**: 343–344.

On the fossils of the American loess see Binney—Proc. Boston soc. nat. hist. **2**: 126–130 (1848); Swallow—Rept. Missouri Geol. surv. **1–2**: 74, 115 (1855); Todd—Proc. Amer. assoc. adv. sci. **27**: 235–236 (1878); Call—Amer. nat. **15**: 585–586, 782–784 (1881), **16**: 380–381 (1882); McGee and Call—Amer. jour. sci. (3) **24**: 202–223 (1882); Chamberlin and Salisbury—Ann. rept. U. S. Geol. surv. **6**, I: 285–286 (1885); Webster—Amer. nat. **22**: 419 (1888); Keyes—Bull. Essex inst. **20**: 61–83 (1888); McGee—Ann. rept. U. S. Geol. surv. **11**, I: 435–471 (1891); Todd—Rept. Missouri Geol. surv. **10**: 129–130 (1896); Bain—Iowa Geol. surv. **7**: 344 (1896); Beyer—ibid., **7**: 237 (1896), **9**: 202 (1898); Leverett—U. S. Geol. surv. Monogr. **38**: 165–176 (1899); Udden—Iowa Geol. surv. **11**: 111–113, 260–265 (1900); Winchell—Bull. Geol. soc. Amer. **14**: 145–146 (1903); M. L. Fuller and Clapp—ibid, pp. 161–163 (1903); I. A. Williams—Iowa Geol. surv. **15**: 327 (1904); Owen—Amer. geol. **35**: 291–300 (1905); and especially Shimek—Amer. geol. **1**: 149–152 (1888); Bull. Lab. nat. hist. Univ. Iowa **1**: 200–214 (1890), **2**: 89–98 (1890), **5**: 195–212 (1901); Proc. Iowa acad. sci. **3**: 82–89 (1895), **4**: 68–72 (1897), **5**: 32–45 (1896), **6**: 98–113 (1898), **7**: 47–59 (1899), **10**: 41–48 (1902), **14**: 237–256 (1907), **15**: 117–135 (1908); Jour. geol. **7**: 122–140 (1899); Amer. geol. **30**: 279–299 (1902); Iowa Geol. surv. **13**: 170–175 (1903). The papers of the last author form the most important and comprehensive American contribution to the subject. His conclusion is that the loessial fauna was almost exclusively terrestrial.

[a] Pub. Carnegie Institution of Washington **54**, vol. 1, pt. I, pp. 252–253 (1907).

by Père David,[a] Pumpelly,[b] Kingsmill,[c] Richthofen,[d] Obruchev,[e] Viglino,[f] Leprince-Ringuet,[g] Wright,[h] and Willis.[i] Similar deposits exist over much of Germany and Austria-Hungary, especially in the river valleys,[j] on the steppes of southern Russia and Turkestan,[k] and in the Mississippi basin in North America,[l] fringing and occa-

[a] Bull. Nouv. arch. Mus. hist. nat. **3**: 18–96 (1867), **4**: 3–82 (1868), **5**: 3–13 (1869), **7**: 75–100 (1871), **8**: 3–128 (1872), **9**: 15–48 (1873), and **10**: 3–82 (1874); Bull. Soc. géog. Paris (6) **9**: 5–45, 131–176 (1875), **11**: 24–52, 156–183, 278–303 (1876). See also his Journal de mon troisième voyage dans l'empire chinois, 1875.

[b] Smithsonian contrib. **15**, IV, 1866; Amer. jour. sci. (3) **17**: 133–144 (1879).

[c] Geol. mag. **3**: 369–370 (1866); Jour. N. China branch Roy. Asiat. soc. (n. s.) **11**: 11–16 (1877); Quart. jour. Geol. soc. **25**: 119–138 (1869), **27**: 376–384 (1871); Nature **47**: 30 (1892); Quart. jour. Geol. soc. **51**: 238–254 (1895); also his Hydraulics of great rivers flowing through alluvial plains, 1906.

[d] Letter on the Province of Hunan, pp. 9–10 (1870); Peterm. Mitth. **17**: 428 (1871); Letter on the Provinces of Chili, Shansi, Shense, etc., pp. 13–18 (1872); Verh. geol. Reichsanst. **1872**: 153–160; Zs. deut. geol. Ges. **25**: 760–763 (1873); Rept. Brit. Assoc. **1873**, II: 86–87; China, vol. **1**, pp. 56–189, vol. **2**, pp. 349–351, 422–427, 530–533, 550–551, and 741–766 (1877); Geol. mag. (2) **9**: 293–305 (1882). See also Schultz—Himmel und Erde **8**: 379–384, 418–428 (1896).

[e] Geog. Zs. **1**: 263–265, 282–285 (1895).

[f] Boll. Soc. geol. ital. **20**: 311–338 (1901).

[g] Ann. mines (9) **19**: 412–429 (1901).

[h] Bull. Geol. soc. Amer. **13**: 127–138 (1902).

[i] Carnegie Inst. of Washington Pub. **54**, vol. **1**, part 1, pp. 183–196, 242–256 (1907).

[j] Lyell—Edinb. New phil. jour. **17**: 110–112 (1834), Antiquity of Man, chap. 16 (1863); Jentzsch—Zs. ges. Naturw. **40**: 1–99 (1872); Richthofen—China, vol. **1**. chap. 5 (1877); Schumacher—Mitt. geol. Landesanst. Elsass-Lothr. **2**: 246–366 (1888); Wahnschaffe—Ursachen des Oberflächengestaltung, pp. 191–196 (1901); and further literature cited in the bibliography under L. Agassiz, Andreae and Osann, d'Archiac, Baltzer, Belt, Bennigsen-Förder, Bömer, Braun, Chelius and Vogel, Courty and Hamelin, Dammer, von Dechen, Dücker, Du Pasquier, Engelhardt, Fallou, Fellenberg, Florschütz, Förster, Foetterle, Früh, Grund, Guembel, Gutzwiller, Hibbert, Horusitsky, Inkey, Jenny, Jentzsch, Keilhack, Klockmann, Kloos, Koken, Leppla, Makowsky, Mousson, Nehring, Nikitin, Penck, von Petrino, Rühl, Sacco, Sachsse and Becker, Sandberger, Sauer, Schréter, Schumacher, Steinmann, Stur, Stürtz, Suess, Tesch, Tietze, Tutkovskiĭ, Van Baren, Viglino and Capeder, Wahnschaffe, van Werveke, Wood, Wüst, and Zeuschner.

[k] Murchison—Geology of Russia, vol. **1**, pp. 561–562 (1845); Belt—Quart. jour. Geol. soc. **33**: 843–862 (1877); Armashevskiĭ—Geological sketch of the Chernigov Govt. (*Russian*), pp. 212–223 (1884), General geological map of Russia, sheet **46**, pp. 255–316 (1903); Hume—Geol. mag. (3) **9**: 549–561 (1892), (4) **1**: 303–307 (1894); Dokoutchaïeff—Bull. soc. belge géol. **6**, Proc. verb.: 97–101 (1892); Capus—Compt. rend. **114**: 958–960 (1892); Tutkovskiĭ—Zemlevíedíenie **1899**: 213–311; Scott. geog. mag. **16**: 171–174 (1900); Pavlov—Bull. Soc. Imp. nat. Moscow (n. s.) **17**: 23–30 (1903); Davis—Carnegie inst. of Washington Pub. **26**: 58–63 (1905).

[l] The northern loess along the border of the ice sheet is described by Chamberlin and Salisbury—Ann. rept. U. S. Geol. surv. **6**, II: 278–307 (1885); McGee—ibid., **11**, I: 291–303 (1891); and Leverett—U. S. Geol. surv. Monogr. **38**: 153–184 (1899); etc. The loess along the lower Mississippi is described by McGee—Ann. rept. U. S. Geol. surv. **12**, I: 392–394 (1891); and Mabry—Jour. geol. **6**: 273–302 (1898); etc. The

sionally overlapping the border of the ice sheet and extending southward along the present river valley. The adobe of the southwestern part of the United States shows many similarities to loess,[a] and the pampas of South America, though as yet not fully investigated, are probably in part of similar material.[b] In areas where it is well developed the loess shows no dependence upon the underlying topography, but covers hill and valley alike in a blanketlike layer, which, it is true, varies in thickness, but according to vagaries of its own or because of secondary denudation and not in relation to the basal relief.

Soils derived from loessial deposits are everywhere among the most fertile in the world. The productiveness of European loess regions has often been noted,[c] and von Hauer[d] states that in Austria exceptional fertility is a sure indication that the soil is loessial. The American loess is not less fertile,[e] and in China the loessial soils have been cropped for 4,000 years without requiring the use of mineral

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many other papers on the American loess are too numerous for review. Those known to the writer (many of which are cited in the following pages) are given in the bibliography under Aughey, Bain, Beyer, Broadhead, Call, Calvin, Calvin and Bain, Campbell, Chamberlin, Chamberlin and Salisbury, Fowke, Fuller and Clapp, C. H. Gordon, C. W. Hall and F. W. Sardeson, Hershey, Hilgard, Keyes, Keyes and Call, Knight, Leonard, Leverett, Lonsdale, Macbride, McGee, Newberry, Norton, Owen, W. H. Pratt, Pumpelly, Savage, Shimek, Todd, Udden (Johan A., and Jon A.), Upham, Webster, C. A. White, Wilder, Willcox, I. A. Williams, Winchell, Witter, and Wright.

[a] I. C. Russell—Geol. mag. (3) **6**: 289–295, 342–350 (1889). Cf. Matthew's ideas with regard to the present formation of "prairie loess" by wind (Amer. nat. **33**: 406–407 [1899]), and Haworth's suggestion regarding the assistance of the wind in the formation of the "plains marl" (U. S. Geol. Surv. Water Sup. pap. **6**: 34 [1897]).

[b] On the Pampas Formation see Bravard—Geología de las Pampas, 1857; Burmeister—Ann. Museo Pub. Buenos Aires **1**: 100–114 (1864–69); Ameghino—La formación pampeana, 1881; Stelzner—Beiträge Geologie Argentinischen Republik, vol. **2**, p. 152 (1885); S. Roth—Zs. deut. geol. Ges. **40**: 375–464 (1888); Brackebusch—Peterm. Mitt. **39**: 157, 162 (1893); Bodenbender—ibid., pp. 231–237, 259–264; Steinmann—Mitt. bad. geol. Landesanst. **2**: 121–123 (1893); N. O. G. Nordenskjöld—Geol. fören. förh. **22**: 191–206 (1900); Burkhardt—Revista Mus. del Plata **14**: 146–171 (1907); Doering—ibid., pp. 172–190 (1907). Bravard believed it to be entirely of eolian origin. Burmeister, Ameghino, Roth, Bodenbender, and Steinmann favor an origin partially eolian and partially aqueous.

[c] Foetterle—Jahrb. geol. Reichsanst. **5**: 884 (1854); Guembel—Geognostische Beschreibung des bayerischen Alpengebirges und seines Vorlandes, p. 797 (1861); Suess—Schrift. Ver. Verb. naturw. Kennt. **6**: 347–348 (1865–66); Stur—Jahrb. geol. Reichsanst. **19**: 468, 482 (1869); Wahnschaffe—Abh. geol. Sp.-Karte Preussen **7**: 79–81 (1885); Puchner—Vierteljahrsch. bayr. Landw.-Rath Munich **8**: 300–308 (1903); Halenke, Kling and Engels—ibid. **10**: 448 (1905).

[d] Die Geologie der österreichisch-ungarische Monarchie, p. 639 (1875).

[e] Pumpelly—Amer. jour. sci. (3) **17**: 135 (1879); Todd—Proc. Iowa hort. soc. **17**: 263–270 (1882); Keyes—Amer. jour. sci. (4) **6**: 302 (1898); Norton—Iowa Geol. surv. **16**: 393–394 (1905); Calvin—ibid. **17**: 5 (1906).

fertilizers.[a] The apparently extraordinary maintenance of full fertility in the last case is, however, partially explained by the prevalent use of night soil, and even more largely by the habit of spreading each year on fields located on the steps of the loess terraces fresh material dug from the perpendicular face of the next higher terrace.[b] A certain amount of new soil material is thus regularly supplied. The material supplied by the frequent dust storms is no doubt also a factor in the maintenance of fertility; in fact, the beneficial action of these storms is well known to the inhabitants both in China itself and in Central Asia.[c] The exceptional fertility of loessial soils in general is, however, unquestioned and is doubtless to be ascribed in part to the unusual degree of heterogeneity[d] entailed by their (partial) eolian origin, but even more largely to the peculiarly good physical texture which they always possess and which allows the free movement and absorption of water, aids the maintenance of good tilth, and encourages a proper sanitary condition in the soil.

THE ORIGIN OF THE LOESS.

The origin of the loess has long been, and to a certain extent still is, a vexed question amongst geologists. The early theories (elaborated with regard to the European loess) ascribed it to the action of great floods following a sudden change of drainage or of sea level.[e] The loess, however, shows no traces of the rapidly moving streams which must have accompanied such a cataclysm, and if aqueous in origin, must have been laid down in still or nearly still waters. Bennigsen-Förder[f] and Fallou[g] advocated a marine origin for the European

[a] Richthofen—Verh. geol. Reichsanst. **1872**: 157, China, vol. **1**, p. 70 (1877). See also Obruchev—Geog. Zs. **1**: 284 (1895).

[b] I am indebted to Dr. Bailey Willis for calling my attention to this custom of the Chinese agriculturists.

[c] See Johnson—Jour. Roy. geog. soc. **37**: 5–6 (1867); Durand—Compt. rend. Assoc. franç. avan. sci. **7**: 476 (1878); Guppy—Nature **24**: 126 (1881); Walther—Einleitung in der Geologie als historische Wissenschaft, p. 575 (1894); Plumandon—Poussières atmosphériques, p. 29 (1897); Chem. trade jour. **43**: 398 (1908).

[d] Obruchev—Geog. Zs. **1**: 284 (1895). Viglino found 54 mineral species in the loess of Shansi (Boll. Soc. geol. ital. **20**: 321 [1901]). See also the less complete mineralogical analyses of the Strassburg loess by Schumacher (Erl. geol. Karte Strassburg, pp. 27–34 [1883]), of the Heidelberg loess by Andreae and Osann (Mitt. bad. geol. Landesanst. **2**: 735–742 [1893]), and of the Piedmont loess by Viglino (Boll. Soc. geol. ital. **17**: 83–84 [1898]).

[e] Hibbert—History of the extinct volcanos of the basin of Neuwied, pp. 183–204 (1832); Guembel—Geognostische Beschreibung des bayerischen Alpengebirges, pp. 798, 805, 852, 872 (1861); Suess—Schrift. Ver. Verb. naturw. Kennt. **6**: 333–348 (1865–66). See also Howorth—Geol. mag. (2) **9**: 9–18, 69–80, 343–356 (1882), **10**: 206–215, 381–384 (1883).

[f] Zs. deut. geol. Ges. **9**: 457–463 (1857), **10**: 215–221 (1858); Das nordeuropäische und besonders das vaterländische Schwemmland, 1863.

[g] Neues. Jahrb. Min. **1867**: 143–158. See also Prestwich—Phil. trans. A, **184**: 919–925 (1894), Geol. mag. (4) **1**: 237–238 (1894).

deposit, and Kingsmill[a] has adopted this theory for the Chinese loess. It is difficult, however, to explain by this means the fact that over many areas, especially in North America and in China, an apparently continuous and uniform sheet of loess is found at altitudes varying amongst themselves by several (or in China, many) hundreds of feet. Nor are there any signs of ancient shore lines or beaches or of marine fossils. These and other less weighty considerations have led to the entire abandonment of the marine hypothesis, at least in application to all loessial deposits of wide extent. There are, however, many localities in which the minor features of the loess speak for some manner of aqueous deposition, and the various forms of the lacustrine and fluvial theories have continued to be held until the present day.[b] The controversies have been waged between, on the one hand, the adherents of these theories, and on the other the followers of Richthofen[c]

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[a] Quart. jour. Geol. soc. **27**: 376–384 (1871). See also references cited on p. 127, note *c*.

[b] Authors favoring the aqueous deposition of loess, probably in lakes or flooded rivers, are: Lyell—Edinb. New phil. jour. **17**: 110–122 (1834), Antiquity of Man, chap. 6 (1863); Charpentier—Essai sur les glaciers et sur le terrain erratique du Bassin du Rhône, 1841; Collomb—Bull. soc. géol. France (2) **6**: 492–499 (1849); Heer—Urwelt der Schweiz, p. 521 (1865); Belt—Quart. jour. Geol. soc. **20**: 463–465 (1864), **30**: 490–498 (1874), **33**: 843–862 (1877), Jour. sci. **7**: 67–90 (1877); Louis Agassiz—Neues Jahrb. Min. **1867**: 676–680; Sandberger—Jour. Landw. **17**: 213–223 (1869), Verh. med.-phys. Ges. Würzburg **14**: 125–140 (1880); C. A. White—Report on the geological survey of Iowa, vol. **1**, pp. 103–117 (1870); Engelhardt—Sitzungsb. Isis Dresden **1870**: 136–141; Jentzsch—Zs. ges. Naturw. **40**: 73–75 (1872), Schr. phys.-ökon. Ges. Königsberg **18**: 161–168 (1877), Verh. geol. Reichsanst. **1877**: 251–258; David—Journal de mon troisième voyage, vol. **1**, p. 94 (1875); C. H. H.—Ausland **51**: 99–100 (1878); Hilgard—Amer. jour. sci. (3) **18**: 106–112 (1879); Broadhead—ibid. 427–428 (1879); Benecke and Cohen—Geogn. Beschreibung Umgebung Heidelberg, pp. 548–573 (1881); Jas. Geikie—Prehistoric Europe, pp. 143–168 (1881); Call—Amer. nat. **16**: 369–381, 542–549 (1882); Wahnschaffe—Abh. geol. Sp.-K. Preus. **7**: 65 (1885), Zs. deut. geol. Ges. **38**: 353–369 (1886), Jahrb. preuss. Landesanst. **1889**: 328–346; Jenny—Mitt. naturf. Ges. Bern **1889**: 115–154; Mills—Amer. geol. **3**: 345–361 (1889); Leppla—Bayer. geognost. Jahresh. **1889**: 176–187, Neues. Jahrb. Min. **1890**, II: 194–198; Upham—Amer. jour. sci. (3) **41**: 33–52 (1891); Erens—Bull. Soc. belge géol. **5**: 38–40 (1891); Dokoutchaïeff—ibid. **6**, Proc. verb.: 97–101 (1892); Hume—Geol. mag. (3) **9**: 549–561 (1892); Todd—Rept. Missouri Geol. surv. **10**: 111–217 (1896) and correspondence with Hershey relating thereto in Science (n. s.) **5**: 587–588, 695–696, 768–770, 993–994 (1897); Calvin—Iowa Geol. surv. **7**: 89–90 (1896); Todd—Proc. Iowa acad. sci. **5**: 46–51 (1897); Hershey—Amer. geol. **25**: 369–374 (1900); Upham—ibid. **31**: 25–34 (1903); Winchell—Bull. Geol. soc. Amer. **14**: 133–152 (1903); Pavlov—Bull. Soc. Imp. nat. Moscow (n. s.) **17**: 23–30 (1903); Norton—Iowa Geol. surv. **16**: 382–386 (1905); Owen—Amer. geol. **35**: 291–300 (1905); Todd—Proc. Iowa acad. sci. **13**: 187–194 (1906); and the monographs of Chamberlin and Salisbury, McGee, and Leverett cited on p. 127, note *d*.

[c] Loci citati on p. 127, note *d*, especially Geol. mag. (2) **9**: 293–305 (1882), Verh. geol. Reichsanst. **1878**: 289–296, and Führer für Forschungsreisende, pp. 477–481 (1886). The eolian theory has been accepted by Tietze—Jahrb. geol. Reichsanst. **27**: 347–350 (1877), Verh. geol. Reichsanst. **1878**: 113–119, **1881**: 37–40, Jahrb. geol. Reichsanst. **32**: 118–132 (1882); Inkey—Földtani Közlöny **8**: 15–26 (1878); Pum-

in his brilliant hypothesis, elaborated with regard to the Chinese loess, which considered it of eolian origin and composed of material carried by the prevailing winds from the dry steppe and desert regions to the west and deposited in its present position both because of loss of wind velocity, due to meteorological determinants, and because of entanglement in the vegetation with which the growing surface is supposed to have been covered. Both the aqueous and eolian theories have some facts in their favor and some in opposition; each has been, and is, held by eminent authorities, and each will require somewhat full consideration.

As a preliminary to such consideration, it may be well to point out that there are really two problems of the loess—a problem of origin of material and a problem of deposition. The loess is composed of very finely comminuted and very uniform material. This must have been the product of some extensive and remarkably efficient disintegrating process, which may conceivably have been aqueous, subaerial, or glacial. Whatever may have been the ultimate source of this material it was probably not produced at the place where it is now found, and search must therefore be made for the agent or agents by which it was transported. These again may have been fluvial, eolian, or glacial. With the source and means of supply fully deter-

pelly—Nation **26**: 231–232, 243–244 (1878), Amer. jour. sci. (3) **17**: 133–144 (1879); Nehring—Globus **37**: 10–11 (1880); Dücker—Verh. naturh. Ver. preuss. Rheinl. Westf. **39**: 234–235 (1882), **40**: 310–311, 423–425 (1883); Hilber—Jahrb. geol. Reichsanst. **32**: 193–330 (1882); Nehring—Geol. mag. (2) **10**: 51–58 (1883); Mühlberg—Progr. Aargau. Kantonschule (1885); Jentzsch—Jahrb. preuss. geol. Landesanst. **1884**: 522–524; Makowsky—Verh. naturf. Ver. Brünn **26**, Abh.: 213–215 (1887); Mushketov—Fizicheskaĭa geol., vol. **2**, pp. 103–108 (1888); Adolf Sauer—Zs. Naturwiss. **62**: 326–351 (1889), Neues Jahrb. Min. **1890**, II: 92–97, Jahresh. Ver. vaterl. Naturk. **57**: cvi–cx (1901); Alfred Sauer—Globus **59**: 24–29 (1891); Shimek—loci citati in bibliography; Klemm—Notizbl. Ver. Erdk. Darmstadt **1892**: 33–38; Steinmann—Mitt. bad. geol. Landesanst. **2**: 120–125 (1893); Andreae and Osann—ibid., pp. 735–742 (1893); Florschütz—Jahrb. nassau. Ver. Naturk. **47**: 123–133 (1894); Gutzwiller—Verh. naturf. Ges. Basel **10**: 678–679 (1895), **13**: 271–286 (1901); Obruchev—Geog. Zs. **1**: 282–285 (1895); Krishtafovich—Post-tertiary deposits of Nova-Alexandria (*Russian*), pp. 40–44 (1896); Udden—Bull. Geol. soc. Amer. **9**: 6–9 (1898), Iowa Geol. surv. **11**: 265–266 (1900); Viglino—Boll. Soc. geol. ital. **17**: 81–84 (1898), **20**: 311–338 (1901); Keyes—Amer. jour. sci. (4) **6**: 299–304 (1898); Horusitzky—Földtani Közlöny **28**: 109–113 (1898); Sachsse and Becker—Landw. Vers.-Stat. **38**: 433 (1898); Sardeson—Amer. jour. sci. (4) **7**: 58–60 (1899); C. W. Hall and Sardeson—Bull. Geol. soc. Amer. **10**: 349–360 (1899); Wilder—Iowa Geol. surv. **10**: 120–122, 145–147 (1899); Früh—Ecl. geol. helv. **6**: 53–59 (1899), Vierteljs. naturf. Ges. Zurich **44**: 157–191 (1899), **48**: 430–439 (1904); Keilhack—Prometheus **10**: 241–246, 263–267, 275–279 (1899); Leprince-Ringuet—Ann. Mines (9) **19**: 368–382, 428–429 (1901); Savage—Iowa Geol. surv. **12**: 294 (1901), **13**: 242–243 (1902), **15**: 529–531 (1904), **16**: 637–639 (1905); Calvin—ibid. **13**: 70 (1902), **16**: 130 (1905); Beyer and Williams—ibid. **14**: 51 (1903); Leonard—ibid. **16**: 287 (1905); Penck—Naturw. Wochens. **20**: 593–597 (1905); Grund—Sitzungsb. Kaiserl. Akad. Wiss. Vienna **115**, I: 550–551 (1906); Łoziński—Jahrb. geol. Reichsanst. **57**: 375–383 (1907); and others.

mined, there remains the problem of deposition, perhaps still more difficult of solution. What were the conditions which enabled the laying down of the supplied silt in a deposit so characteristic and so widespread as the loess?

It is, of course, obvious that the agents of supply and of deposition need not have been the same. The débris of secular rock decay may have been sorted and carried by the wind and the finer silt dropped into lakes where the deposit was being formed. Or the silt may have been carried by flooded rivers, deposited on their flood-plains, dried, and blown away to the areas of accumulation. Or, even more complexly, rock flour produced by glacial grinding may have been spread out on the marginal plains or left behind by the retreating ice and redistributed and deposited by either wind or water or both. Any particular deposit of loess, instead of being the product of the action of water, wind, or ice, may conceivably have been formed by any pair of them or by all three acting either simultaneously or in succession.

It is also well to note that whatever may be the uncertainties as to the agent or agents of loess production, the chronology of the formation is fairly well fixed. Innumerable indications connect it with the glacial period and probably with the stages of retreat or decay of the ice sheet. These indications are clearer and more certain in North America than elsewhere, but are also unmistakable in Europe and probably not less apparent in China, though in the latter country the detailed investigation of Pleistocene geology is still in its infancy. The evidence includes not only the position of the loess in the stratigraphic series, but the parallelism (in North America) of the belt in which it is developed with the margin of the ice sheet and the not infrequent interstratification of loess with marginal drift and till of undoubted glacial origin.[a] It seems very probable that there were several subperiods of loess formation all lying within the glacial epoch and each related to one of the successive periods of retreat of the ice sheet. That the American loess was deposited at the time of glacial retreat is believed by the authors of the three most thorough and

[a] Winchell—Ann. Rept. Geol. nat. hist. surv. Minn. **6**: 105 (1878), Amer. geol. **31**: 279–282 (1903), Bull. Geol. soc. Amer. **14**: 141–142 (1903); McGee—Proc. Amer. assoc. adv. sci. **27**: 198–202 (1878), Bull. Phil. soc. Wash. **6**: 93–97 (1883), Ann. rept. U. S. Geol. surv. **11**, I: 435–471 (1891); Chamberlin and Salisbury—Ann. rept. U. S. Geol. surv. **6**, I: 287 (1885); Todd and Bain—Proc. Iowa acad. sci. **2**: 20–23 (1894); Bain—Iowa Geol. surv. **5**: 283–284 (1895), **7**: 342–343 (1896), **9**: 89–91 (1898); Hershey—Amer. geol. **17**: 294–298 (1896); Leonard—Iowa Geol. surv. **8**: 87 (1897); Beyer—Proc. Iowa acad. sci. **6**: 117–121 (1898); Shimek—Bull. Geol. soc. Amer. **16**: 589 (1906); and other references given by M. L. Fuller and Clapp—Bull. Geol. soc. Amer. **14**: 174–176 (1903).

comprehensive works dealing with the region in question,[a] and this opinion has been generally accepted by geologists. Its validity, however, is as a general principle only, for there are undoubtedly occasional deposits of loess of secondary, and perhaps of primary, origin which are much later in date.

Turning now to a consideration of the evidence behind the eolian and the aqueous hypotheses, respectively, it will be advisable to discuss first the manner of deposition, as it is this which is largely responsible for the peculiarities of the deposit and because it is over this problem rather than over the problem of source that the controversies have been waged. Postponing until later the mention of those instances in which loessial material is now accumulating by whatever agency, it is found that the most important single item of evidence in favor of the eolian hypothesis is the terrestrial character of the loessial fauna. The occurrences of other than land fossils are sporadic and perhaps adventitious, and there can be no question that the vast majority of the organic remains of the loess are those of animals which lived altogether on land. The mere presence of land-shells in fluvial, lacustrine, or marine deposits is of course nothing extraordinary, but the absence of aqueous forms from fossiliferous strata of such origin would be very remarkable indeed. It is not the occurrence of terrestrial forms but the nonoccurrence of any others that seems to favor so strongly the deposition of the loess over a dry land surface. Some advocates of the aqueous hypothesis have endeavored to explain the character of the loessial fossils by assuming that they are not contemporaneous with the loess, but have reached their position therein by secondary movements of the material; by falling into cracks or animal burrows from the present surface, etc.[b] Such phenomena can hardly be of very general occurrence, and in any event they could explain only the presence of terrestrial forms and not the absence of the aqueous (unless the original deposit be assumed totally nonfossiliferous). More plausible is the suggestion that the aqueous

[a] Namely: Chamberlin and Salisbury—The driftless area of the Upper Mississippi, Ann. rept. U. S. Geol. surv. **6**, I, especially pp. 305–306 (1885); McGee—The Pleistocene history of Northeastern Iowa, Ann. rept. U. S. Geol. Surv. **11**, I, especially p. 462 (1891); Leverett—The Illinois Glacial lobe, U. S. Geol. Surv. Monogr. **38**, especially pp. 176–177 (1899). See also Todd—Proc. Iowa acad. sci. **1875–80**: 19; Calvin—Iowa Geol. surv. **7**: 88–90 (1896), Bull. Geol. soc. Amer. **10**: 118–120 (1899); Bain—Iowa Geol. surv. **7**: 342–343, 463–466 (1896), **9**: 91–92 (1898); Savage—ibid. **13**: 242 (1902), **16**: 637 (1905); Leverett—Amer. geol. **33**: 56–57 (1904); I. A. Williams—Iowa Geol. surv. **15**: 326–327 (1904); Leonard—ibid. **16**: 287 (1905); Norton—ibid. **16**: 386 (1905).

[b] Kingsmill—Quart. jour. Geol. soc. **27**: 379–380 (1871); Chelius—Notizbl. Ver. Erdk. Darmstadt **1892**: 21–23; Todd—Proc. Iowa acad. sci. **13**: 192 (1906). For opposing opinion see Shimek—ibid. **14**: 237–256 (1907).

deposition may have been intermittent—as on the flood-plains of rivers—and that in the intervals of no deposition and of exposure to the air the fauna driven out (or perhaps up the stalks of plants) by the inundation had time to return and repopulate the area, providing potential fossils for the next period of deposition.[a] It is probable that this explanation is valid in certain cases, but it is hard to see how intermittent deposition of this character could take place without leaving distinct traces of stratification or lamination, and such traces are by no means general in the American loess and are very rare in that of China.

This absence of stratification, the great uniformity of the deposit, and in general the lack of the traces of water action so characteristic of ordinary sedimentary deposits is in itself another strong argument for the eolian hypothesis. It is possible that material deposited in permanent and nearly currentless lakes or in very sluggish rivers might show no traces of water action, but such material, if fossiliferous at all, should show a fresh water fauna with only occasional terrestrial examples. Continuous aqueous deposition can not explain the terrestrial fauna, and intermittent flood-plain deposition is probably inconsistent with the absence of stratification and other traces of water action.

On the other hand, the aqueous hypothesis is favored by the unmistakable relation of much loess, especially in North America, to the stream valleys.[b] This is true not alone in horizontal but also in vertical projection. The belt of loess is not only more or less parallel to the stream, but is often thicker near its banks, forming a natural levee and indicating deposition from flood waters flowing outward from the channel and rapidly losing their load because of loss of velocity and by entanglement in vegetation. This process has been observed along the course of all overloaded rivers through their flood plains and has usually, and probably rightly, been assumed characteristic of such conditions. Shimek[c] has urged, however, that even eolian loess would be thicker along stream courses because there the vegetation would be more extensive, more vigorous, and more permanent, and consequently more dust would be entangled and retained.[d]

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[a] Jentzsch—Zs. ges. Naturw. **40**: 1–99, especially 73–75 (1872); Sandberger—Verh. med.-phys. Ges. Würzburg **14**: 125–140 (1880); Winchell—Bull. Geol. soc. Amer. **14**: 145–146 (1903).

[b] Chamberlin—Jour. geol. **5**: 795–802 (1897).

[c] Bull. Lab. nat. hist. Univ. Iowa **5**: 319 (1904).

[d] An actual occurrence of this sort is described from Central Asia by Przhevalskiĭ (Kulja to Lob Nor, p. 57 [1879]). Cf. also the suggestion of Savage (Iowa Geol. surv. **15**: 531 [1904]) that the thicker deposits along rivers may be due to the blowing of dust from dried river bars and flats.

A more certain indication of aqueous deposition is the undoubted presence in some occurrences of loess of well-developed strata, and intergradations of finer and coarser material,[a] which appearances can be ascribed to nothing else than deposition from water. These strata can by no stretch of the imagination be considered similar to the false bedding of eolian sands, and the evidence is perfectly conclusive for those deposits from which it has been obtained.

These apparently contradictory conclusions can be reconciled only by the obvious deduction that the manner of deposition of the loess was not everywhere the same. There is both eolian loess and aqueous loess, and it is quite conceivable that there is loess which is both aqueous and eolian. Loess is no more a specific thing than is sandstone, or shale, or conglomerate; and as there are sandstones which have been formed from dunes, or by rivers, or in the sea, so there are "loesses" which are eolian, or fluvial, or (perhaps) marine. "The time for generalization as to origin of the loess as a whole from observations in a single region appears to have passed, and the origin in each locality is best decided for itself by its own internal or physiographic evidence."[b]

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[a] Hilgard—Report on the Geology and Agriculture of Mississippi, pp. 194–197 (1860), Amer. jour. sci. (3) **18**: 106–112 (1879); Hayden—Rept. Geol. surv. Terr. **1**: 10, 12, 18, 19 (1867); Safford—Geology of Tennessee, pp. 114, 433–434 (1869); Jentzsch—Schr. phys.-ökon. Ges. Königsberg **18**: 163–164 (1877); Todd—Proc. Amer. assoc. adv. sci. **26**: 287–291 (1877), **27**: 231–239 (1878), Proc. Iowa acad. sci. **5**: 46–51 (1897), U. S. Geol. surv. Bull. **158**: 65–68 (1899); Broadhead—Amer. jour. sci. (3) **18**: 427–428 (1879); Schumacher—Erl. geol. Karte Umgeb. Strassburg, pp. 13–19 (1883); Chamberlin and Salisbury—Rept. U. S. Geol. surv. **6**, I: 281, 283–284, 287 (1885); Uhlig—Jahrb. geol. Reichsanst. **34**: 212 (1884); Witter—Proc. Iowa acad. sci. **1**: 45 (1890); McGee—Ann. rept. U. S. Geol. surv. **11**, I: 445–446, 469–470, et al. (1891); Kloos—Zs. deut. geol. Ges. **44**: 327–328 (1892); Leverett—Amer. geol. **10**: 18–24 (1892), Rept. Ill. Board World's Fair Com., pp. 82–83 (1895), U. S. Geol. surv. Monogr. **38**: 156–184 (1899); Whitney—Rept. Ill. Board World's Fair Comm., p. 101 (1895); Shimek—Proc. Iowa acad. sci. **3**: 82–89 (1895); Norton—Iowa Geol. surv. **4**: 173 (1894), **9**: 485 (1898), **16**: 377 (1905); Beyer—ibid. **7**: 235 (1896); Bain—ibid. **7**: 341 (1896); Calvin—ibid. **8**: 174 (1897); Chamberlin—Jour. geol. **5**: 795–802 (1897); Früh—Vierteljahrsch. naturf. Ges. Zurich **44**: 172 (1899); Hershey—Amer. geol. **25**: 369–374 (1900); M. L. Fuller and Clapp—Bull. Geol. soc. Amer. **14**: 153–176 (1903); Winchell—ibid. **14**: 143–145 (1903); Beyer and Young—Iowa Geol. surv. **13**: 380 (1902); Darton—U. S. Geol. surv. Prof. pap. **17**: 15–16 (1903); Wright—Amer. geol. **33**: 205–222 (1904), **35**: 236–240 (1905); Owen—ibid. **33**: 223–228 (1904). On stratified loess in China see: Wright—Bull. Geol. soc. Amer. **13**: 132 (1902); and in Turkestan see Capus—Compt. rend. **114**: 959 (1892).

[b] M. L. Fuller and Clapp—Bull. Geol. soc. Amer. **14**: 174 (1903). The action of both wind and water in loess formation has been recognized by Richthofen himself (Rept. Brit. Assoc. **1873**, II: 86–87, Verh. geol. Reichsanst. **1878**: 289–296); by Chamberlin and Salisbury, McGee, and Leverett in the monographs cited on p. 133, note *a*; and by Jentzsch—Schr. phys.-ökon. Ges. Königsberg **18**: 167 (1877), Verh. geol. Reichsanst. **1877**: 258; Tietze—ibid., p. 264; Nehring—ibid. **1878**: 261–272, Tundren und Steppen, pp. 217–221 (1890); Call—Amer. nat. **16**: 369–381, 542–

All this concerns mainly the agent or agents by which the loessial material was deposited. A word now as to the source of the material itself. It would seem that only in two ways could such a large amount of finely comminuted débris have been produced—either by long-continued secular decay of the rock with accompanying removal of the débris, or by the grinding of moving ice. In either case the material has undoubtedly undergone a remarkably efficient sorting process either by wind or water or by both. With regard to the American deposits the weight of evidence and opinion seems to favor the conclusion that the loessial material is probably rock flour from under the ice sheet.[a] The physical properties of the loessial grains are quite consistent with such an origin, and it is known that much material was prepared and supplied in this way. It is by no means necessary, however, to assume that glacial débris is the exclusive material of the formation. Insolation and rock decay are now very active in the drier region west and southwest of the loess-covered areas, and were probably not less so in the past. It is possible that much dust thus formed has been removed by the wind from these regions and carried into the regions of loessial deposition. Thus with regard to source of materials, as with regard to manner of deposition, not all loessial deposits are the same, and perhaps not all the materials of any one deposit are the same. There is no known criterion which will enable the distinguishing of glacial silt from silt formed by rock decay (especially insolational decay); nor is the completeness of the sorting any indication of the nature of the elutriating agent, for water and wind, though different in action, are equally

549 (1882); von Lasaulx—Encyc. Naturw., Abt. II, **1**: 78 (1882); Penck—Arch. Anthropol. **15**: 222–225 (1884); Fellenberg—Mitth. naturf. Ges. Bern **1885**: 34–43; Rzehak—Sitzungsb. naturf. Ver. Brünn **26**: 34 (1887); Schumacher—Mitth. geol. Landesanst. Elsass-Loth. **2**: 314–366 (1888–90); Nikitin—Bull. Com. géol. St. Petersburg **5**: 133–185 (1886); Du Pasquier—Beitr. geol. Karte Schweiz **31**: 57 (1891); Chelius and Vogel—Neues Jahrb. Min. **1891**, I: 104–107; Hume—Geol. mag. (3) **9**: 557–561 (1892), (4) **1**: 303–307 (1894); Capus—Compt. rend. **114**: 958–960 (1892); Steinmann—Mitt. bad. geol. Landesanst. **2**: 745–791 (1893), Verh. deut. geol. Ges. **50**: 88–98 (1899); Tutkovskĭĭ—Ann. géol. min. Russie **2**, I: 60–63 (1896), **3**, I: 117 (1898), **4**, I: 108–109 (1899); Chamberlin—Jour. geol. **5**: 795–802 (1897); Keilhack—Prometheus **10**: 278 (1899); Sauer—Jahresh. Ver. vaterl. Naturk. **57**: cvi–cx (1901); Gutzwiller—Verh. naturf. Ges. Basel **13**: 271–286 (1901); Wright—Quart. jour. Geol. soc. **57**: 245 (1901), Bull. Geol. soc. Amer. **13**: 127–138 (1902); Krishtafovich—Verh. Imp. min. Ges. St. Petersburg (2) **40** Protokol: 98–100 (1903); Todd—Proc. Iowa acad. sci. **13**: 187–194 (1906); Willis—Carnegie Inst. Washington Pub. **54**, vol. **1**, part 1: 245–249 (1907); Stürtz—Verh. naturh. Ver. preuss. Rheinl. Westf. **64**: 84–85 (1907); and others. M. L. Fuller and Clapp (Bull. Geol. soc. Amer. **14**: 153–176 [1903]) have worked out in a most interesting way the conditions in the Wabash Valley and shown that in this locality there are two general types of the loessial formation, one of which is mainly eolian, the other mainly aqueous.

[a] See, for example, Chamberlin and Salisbury—Ann. rept. U. S. Geol. surv. **6**, I: 287, 304–305 (1885).

efficacious in this regard and give equally perfect results. The grains of loess are usually angular, but this condition is a property of insolational and glacial silts alike, and is consistent with either aqueous or eolian transport, for by either agent material so fine as the loess is carried in a nearly permanent suspension and undergoes but little abrasion.

The decision as to source must therefore rest upon external and not internal evidence, upon the general geologic indications as to probable areas, and agents of supply. It is for this reason that the hypothesis of predominantly glacial origin is preferred in the case of the North American loessial materials. The existence and operation of the glacial grinding mill is a known fact, while it is difficult to locate on the North American continent any areas of deflational removal sufficiently extensive and subject to sufficiently rapid degradation to provide the enormous mass of material which exists.[a] In China the conditions are reversed, and there it is the glaciers which are apparently lacking,[b] while a very extensive area of eolian removal is still to be seen in the dry region in and contiguous to the Desert of Gobi. It is therefore probable that Pumpelly[c] is correct in his conclusion that the materials of the Chinese loess are mostly the aerially transported débris of central Asian rock decay and only in very small proportion the silt of glaciers. The European loess, like the American, is probably largely glacial, though it would be unwarrantable to altogether exclude silts of other origin.

In a very general way, then, the primary American deposits of loess may be considered as made up mostly of glacial silt, but partly of wind-borne rock débris from the arid regions to the west, these two materials, separate or mixed, having been collected or deposited either by eolian action, or on the flood-plains of great but sluggish

[a] Climatic conditions were probably quite different during Glacial time, and it is possible that arid areas of deflational removal were then more numerous or more extensive than to-day. It has, in fact, been suggested on meteorologic grounds that the presence of the ice sheet would in itself cause the prevalence of aridity over certain contiguous or neighboring areas and that these areas might have been the places of origin of the loessial material. On these matters, see Nehring—Sitzungsb. Ges. Naturfr. **1889**: 189–196, and Über Tundren und Steppen (1890), Globus **65**: 365–370 (1894); Jamieson—Geol. mag. (3) **7**: 70–73 (1890); Reid—Bull. Soc. belge géol. **7**, Proc. verb.: 193–198 (1893); Krause—Globus **65**: 1–6 (1894); Geikie—Scott. geog. mag. **14**: 281–294, 346–357 (1898); Tutkovskiĭ—ibid. **16**: 171–174 (1900); Sauer—Jahresh. Ver. vaterl. Naturk. **57**: cvi–cx (1901); Vahl—Geog. tids. **16**: 173–183 (1902); Penck—Res. scient. Cong. intern. bot. **1905**: 12–24, Geog. jour. **27**: 182–187 (1906); Grund—Sitzungsb. Kaiserl. Akad. Wiss. Vienna **115**: 551 (1906); Romer—Verh. geol. Reichsanst. **1907**: 48–55; Łoziński—Jahrb. geol. Reichsanst. **57**: 375–383 (1907); Jentzsch—Monatsb. deut. geol. Ges. **1908**: 120–123; and the further literature cited by these authorities.

[b] Wright—Bull. Geol. soc. Amer. **13**: 127–138 (1902).

[c] Amer. jour. sci. (3) **17**: 133–144 (1879).

rivers, or perhaps in more or less permanent shallow lakes. It is possible that in certain isolated localities deposits of loessial character may owe their existence to rain wash,[a] to the sea, or to other complex and unusual factors,[b] but such cases are uncommon, and even lacustrine deposition was probably quite rare, being apparently excluded (as already described) by the character of the fossil fauna. Most American loess is probably either wind-deposited or laid down by the intermittent floods of muddy rivers.

The determination of the exact origin of any particular deposit of loess must await the careful survey of its physical, geographical, and geological characteristics, and in the lack of such detailed and accurate surveys of the loessial areas it is manifestly impossible to say how much of the work of loess formation in general was done by water and how much by wind. Estimates based on the meager data at present available could have no worth whatever. It is probable, however, that the loess over many areas is predominantly or exclusively eolian,[c] and the loessial materials are so readily susceptible to wind action that even in other areas it seems not improbable that loess with which the eolian agencies have had nothing at all to do is a rare exception. Some loess is altogether wind-formed and all loess is probably somewhat wind-formed.

As a possible suggestion toward an explanation of the mechanism by which glacial silt may have been distributed and deposited by the wind, mention should be made of the fact noted by many writers, and with especial clearness by Tutkovskiĭ,[d] that the retreating ice sheet would be bordered by a vegetationless and exposed area covered with disintegrated material and probably subject to the maxi-

[a] Baltzer—Mitth. naturw. Ges. Bern **1885**, III: 124–127; Sacco—Bull. Soc. géol. France (3) **16**: 229–243 (1887); Koken—Neues Jahrb. Min. **1900**, II: 167–169; de Lapparent—Bull. soc. géol. France (3) **13**: 456–461 (1885), Traité de géol., 4th ed., pp. 1610–1611 (1900). Jenney (School of Mines quart. **10**: 316–318 [1889]) has observed a loesslike deposit formed by the rain wash of mountain silt into the dry lake basins of the arid west. On deposits of loess formed by rain wash in southern Russia and Turkestan, see Armashevskiĭ—Mém. Soc. nat. Kiev **7**: 212–223 (1884), ibid. **15** Proc.-verb.: lv, lxxviii (1896); and Capus—Compt. rend. **114**: 958–960 (1892). The adobe, as already mentioned, is quite similar to loess and has probably been formed by the joint action of rain wash and wind. See Russell—Geol. mag. (3) **6**: 289–295, 342–350 (1889).

[b] As, for instance, the flow of saturated soil, especially after thawing, as advocated by Wood—Geol. mag. (2) **9**: 339–343, 411–416 (1882), **10**: 389–397 (1883). On secondary slipping of loess, see also Todd—Proc. Iowa Acad. Sci. **13**: 192 (1906), Geol. Atlas U. S., folio **156**: 3 (1908).

[c] The occurrence in the loess of sand-polished bowlders as observed by Wilder (Iowa Geol. surv. **10**: 120–122 [1899]), or of sand-masses showing eolian cross-bedding as observed by Calvin (ibid. **11**: 444–446 [1900]), furnishes a nearly perfect proof that the wind had much to do with the genesis of those particular deposits, at least.

[d] See the exposition of his views in the Scott. geog. mag. **16**: 171–174 (1900). See also Łoziński—Jahrb. geol. Reichsanst. **57**: 375–380 (1907).

mum of eolian action. From this "zone of deflation" dust would be carried outward into what Tutkovskiĭ calls the "zone of inflation," or of accumulation lying farther away from the glacial border. Udden's [a] suggestion of the possibility of loess accumulation in the great snow field or *névé* which probably fringed the ice sheet may also have its place in a complete theory of the loess, though Davison's [b] idea that all loess was deposited in snow drifts is certainly extreme and untenable.

The features of the formation in Europe are probably not essentially different from those in North America,[c] but in China it seems that the share of the wind in loess formation has probably been much greater, especially (as already indicated) in the transportation of the material from the region of production in central Asia to the localities where it is now found. The geographical positions of the areas of loess accumulation may have been in part determined by the vegetation there growing which entangled and retained the dust, but are more likely to have been fixed by meteorological factors controlling the path and strength of the dust-bearing winds and especially the areas over which they habitually decreased in velocity and began to deposit their load.

Neither the action of the wind nor that of water on the loessial material has stopped with the primary deposition. Being in most localities a surface deposit, the formation has been much moved and removed, and sorted and resorted by winds and rains and streams. Thus there have been produced many secondary deposits of loess, some of them clearly wind-formed, some just as clearly the product of stream action, and some in which the agent or agents of rearrangement are recognizable only with difficulty if at all. These secondary rearrangements have not stopped with the beginning of the present era but are still continuing, and there are indeed deposits apparently of primary character which are still increasing under the action of wind or water, or both. Thus rivers like the Nile, the Mississippi, the Ganges, the Po, the rivers of eastern China, and others which periodically pour muddy floods over their alluvial plains are in this way depositing flood-plain loess,[d] while the present-day activity of the eolian agencies is instanced by the observations of Shaler[e] on the blown loessial deposits along the streams in the arid portions

[a] Jour. geol. **10**: 250–251 (1902).

[b] Quart. jour. Geol. soc. **50**: 472–487 (1894).

[c] The European conditions are summarized by Richthofen—China, vol. **1**, pp. 153–173 [1877]. For occurrences of undoubted eolian loess in Germany, see Sauer and Siegert—Zs. deut. geol. Ges. **40**: 580 (1888); Sauer—Zs. Naturwiss. **62**: 326–351 (1889); and the authors cited on p. 130, note *c*.

[d] On the present-day deposition of loess by small streams see Todd—Proc. Iowa acad. sci. **14**: 257–266 (1907).

[e] Bull. Geol. soc. Amer. **10**: 245–252 (1899).

of Montana; of Beyer[a] on the continual accumulation of dust on top of the stream-valley bluffs of Iowa; of Keyes[b] and of Shimek[c] on the recent loess formed of dust blown from the flats of the Missouri River; and of Matthew[d] and of Reagan[e] on the present formation of eolian loess on the Great Plains and in New Mexico, respectively.

In China and Central Asia the accumulation of eolian loess at the present time and within the historic past has been observed by Richthofen,[f] Lóczy,[g] Obruchev,[h] Hedin,[i] Ivchenko,[j] Huntington,[k] R. W. Pumpelly,[l] and Stein.[m] Recent eolian deposits of loesslike material have been described by Stur[n] from the high Alps, by Virlet d'Aoust[o] from the Mexican highlands, by Thoroddsen[p] from Iceland, by Tietze from Persia,[q] by Lyons[r] and Grund[s] from certain parts of the Sahara, by Philippi[t] from South Africa, and by Hundhausen[u] from New Zealand. Van den Broeck[v] ascribes an eolian origin to the loesslike loam ("limon hesbayen") of Belgium. The dust storms of 1887–1888 in Saxony produced deposits of loesslike material in some places as much as 3 or 4 centimeters thick.[w] The resorting of old loess by the wind is also very common in loess regions and has been observed in China by Wright[x] and by

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[a] Proc. Iowa acad. sci. **6**: 117–121 (1899).

[b] Amer. jour. sci. (4) **6**: 299–304 (1898).

[c] Iowa Geol. surv. **13**: 174–175 (1902). Cf. Amer. geol. **3**: 397–398 (1889); and C. G. Hopkins and Pettit—Ill. agr. expt. stat. Bull. **123**: 238 (1908).

[d] Amer. Nat. **33**: 406–407 (1899).

[e] Science (n. s.) **28**: 653 (1908).

[f] China, vol. **1**, p. 150–151 (1877).

[g] Reise des Grafen Széchenyi, vol. **1**, p. 421 (1893).

[h] Verh. Imp. min. Ges. St. Petersburg (2) **33**: 263–269 (1895).

[i] Scientific results, vol. **1**, pp. 291–293 (1904).

[j] Ann. géol. min. Russ. **7**, I: 221–222 (1904).

[k] Bull. Geol. soc. Amer. **18**: 359–360 (1907), Pulse of Asia, pp. 91, 103, 134–135, 156–157 (1907).

[l] Carnegie Inst. of Washington Pub. **73**, vol. **2**: 271 et al. (1908).

[m] Geog. jour. **34**: 13, 14 (1909).

[n] Verh. geol. Reichsanst. **1872**: 185.

[o] Bull. Soc. géol. France (2) **15**: 129–139 (1857); Compt. rend. Soc. géog. Paris **1885**: 464–466. See also Meunier—La Nature **2**, II: 26–27 (1874).

[p] Peterm. Mitt. **31**: 338 (1885).

[q] Jahrb. geol. Reichsanst. **27**: 348 (1877), **31**: 80–85 (1881).

[r] Quart. jour. Geol. soc. **50**: 537 (1894).

[s] Sitzungsb. Kaiserl. Akad. Wiss. Vienna **115**: 545, 549, 551 (1906).

[t] Zs. deut. geol. Ges. **56**, Monatsb. 66: (1904).

[u] Globus **90**: 47 (1906).

[v] Bull. Soc. belge géol. **1**, Proc.-verb.: 151–159 (1887), **2**, Proc.-verb.: 188–192 (1888).

[w] Sauer and Siegert—Zs. deut. geol. Ges. **40**: 575–582 (1888). See p. 102 above.

[x] Bull. Geol. soc. Amer. **13**: 127–138 (1902).

Skertchly and Kingsmill,[a] in southeastern Russia by Hume,[b] and in the Mississippi Valley by Todd,[c] Williams,[d] and Savage.[e]

EOLIAN ACTION DURING PRE-PLEISTOCENE TIME.

Though there is no reason to believe that the wind has been generally less active in the past than it is to-day, very few formations possessing unmistakable indications of eolian origin are known in the stratigraphic series. This rarity is probably in some measure apparent and due to specific search not having been made for signs of wind action, but it is no doubt largely real and indicative of an actual lack of wind-formed strata. Some such lack is to be expected. The sea is par excellence the place for strata building and the majority of preserved deposits are naturally marine. As already explained, eolian action does not in general lead to the formation of characteristic and recognizable accumulations, and in the comparatively rare cases in which such are produced they are subject to rapid subaerial denudation, and have a far less than normal expectancy of being preserved as a part of the geologic column. Further, the recognition of eolian origin is so largely dependent upon external and evanescent criteria to which the internal characteristics of the strata offer so little assistance, that the indications of wind action must have been very clear and striking to have survived the various metamorphic changes which accompany consolidation and lithification.

Such loessial deposits as may have been formed in periods previous to the last ice invasion have probably been either entirely removed by the denuding agencies or else so completely altered by processes of induration and metamorphism as to render impossible any recognition of the manner of origin. It is apparent from the previous pages that even in the deposits of this character belonging to the present era the criteria of eolian or of aqueous origin, particularly such of these criteria as depend upon internal evidence alone, are by no means unmistakable.

Dune sands have, however, certain characteristics, such as great purity and uniformity, perfect rounding of the grains, irregular false bedding,[f] eolian ripple marks, etc., which are likely to persist through

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[a] Quart. jour. Geol. soc. **51**: 238–254 (1895).

[b] Geol. mag. (3) **9**: 549–561 (1892).

[c] Proc. Iowa acad. sci. **1875–80**: 21.

[d] Iowa Geol. surv. **16**: 497 (1905).

[e] Ibid. **16**: 638–639 (1905). Cf. the eolian resorting of river-deposited silt in Khotan (Stein—Ancient Khotan, pp. 124–125, 198, and Appendix G [by Lóczy], 1907).

[f] See: Tietze—Verh. geol. Reichsanst. **1877**: 265; Briart—Bull. Soc. géol. France (3) **8**: 586–591 (1880); Reade—Geol. Mag. (2) **8**: 197–198 (1881); Tenison-Woods—Jour. Proc. Roy. soc. N. S. Wales **16**: 53–88 (1882); Grabau—Science (n. s.) **25**: 296 (1907). The characters and occurrences of the various kinds of stratification which are possible in eolian deposits have been well discussed by Ivchenko—Ann. géol. min. Russie **10**, I: 18–27 (1908).

ordinary metamorphic changes; and it has therefore happened that, partly on such internal evidence and partly on general geologic data, certain formations have been more or less perfectly identified as formed by the consolidation of masses of drifting sand. Among the best examples of such fossilized dune complexes are the Saint Peter and the Sylvania sandstones of the northern Mississippi Valley, the former of which is believed by Berkey [a] to be the result of the joint action of wind and wave along the sandy coast of a slowly retreating arm of the sea; while the latter, according to Grabau and Sherzer,[b] represents sands weathered from previous sandstone rocks (possibly the Saint Peter itself) and much drifted and arranged by the wind. On account of its history of long attrition and assorting, partly by water but especially by wind, the Sylvania possesses to a remarkably high degree the characteristics of purity, rounded grains, etc., which mark an eolian rock. A similar origin from an area of coastal sands is ascribed by A. W. G. Wilson [c] to the band of gray sandstone stretching across Ontario from Niagara Falls to Collingwood, and by Huntington and Goldthwait [d] to the Kanab and Colob formations (probably Permian) of southwestern Utah and northwestern Arizona. From its analogies with certain recent eolian limestones of India, Evans [e] suggests that the Great Oolite series of England may be eolian. The Triassic reptiliferous sandstone of Elgin, Scotland,[f] and the Triassic strata of England in general,[g] the Hawkesbury sandstone of Australia,[h] the sandstones of Rambouillet (France),[i] and the Nubian sandstone (Cretaceous) of Egypt,[j] all show indications of eolian action, but in no case is the evidence perfectly conclusive. Old dune areas underlying the loess along the border of the Iowan drift have been found by Shimek,[k] and Parran [l] has described from

[a] Bull. Geol. soc. Amer. **17**: 229–250 (1906). Cf. Grabau—Jour. geol. **17**: 249–250 (1909). Calvin dissents, ibid., p. 250.

[b] In a paper as yet unpublished. I am indebted to Professor Sherzer for the opportunity of examining the preliminary draft. An abstract (by Grabau) is published in Science (n. s.) **26**: 832 (1907). See also Grabau—loc. cit. supra.

[c] Canad. rec. sci. **9**: 120–122 (1903).

[d] Bull. Mus. comp. zool. **42**: 214–216 (1904). See also Huntington—Bull. Geol. soc. Amer. **18**: 384–388 (1907).

[e] Quart. jour. Geol. soc. **56**: 578–580 (1900).

[f] Mackie—Trans. Edinb. geol. soc. **7**: 166 (1897).

[g] See p. 145 below.

[h] Tenison-Woods—Jour. Proc. Roy. soc. N. S. Wales **16**: 53–116 (1882).

[i] Meunier—Compt. rend. **85**: 1240–1242 (1877).

[j] Walther—Verh. Ges. Erdk. Berlin **15**: 253 (1888); Blanckenhorn—Geologie Ägyptens, p. 27 et seq. (1901); Fourtau—Compt. rend. **135**: 803–804 (1902). A marine origin is favored by Hume—Topography of Southeastern Sinai, p. 153 (1906).

[k] Bull. Lab. nat. hist. Univ. Iowa **5**: 357 (1904).

[l] Bull. Soc. géol. France (3) **18**: 245–251 (1890).

the northern coast of Africa some dunes which he believes to be of Pliocene age.

Other examples of ancient, though perhaps not pre-Pleistocene dunes have been described from many parts of the world,[a] and the layers of soil often found covering dune sands and interstratified with them [b] indicate a previous and interrupted activity of the agents of dune production. In fact it is probable, as Braine [c] believes to be the case in South Africa, that sand movement and dune production is likely to be intermittent, periods of rest and of soil formation alternating with periods of active sand-drift.[d] Resting sand dunes which are calcareous or contain any calcareous material are soon consolidated by the action of percolating waters,[e] and important deposits of eolian rock (so far as known of comparatively recent age) have been produced in this way.[f] Such rocks formed from coral

[a] Good examples are the observations of Kennard and Warren in Cornwall (Geol. Mag. (4) **10**: 19–25 [1903]), or of Solger in northern Germany (Verh. deut. Geog.-Tags **15**: 159–172 [1905], Zs. deut. geol. Ges. **57**, Monatsb.: 179–190 [1905], Monatsb. deut. geol. Ges. **1908**: 54–59). In connection with these last observations see also Romer—Verh. geol. Reichsanst. **1907**: 48–55, and literature there cited. Durègne has discovered that there are two superposed dune systems in Gascony, one ancient and one recent (Compt. rend. **111**: 1006–1008 [1890], Actes Soc. linn. Bordeaux **57**: 1–10 [1902], and other articles cited in the bibliography). See also Fabre—Compt. rend. **135**: 1134–1135 (1902). Klemm has made an analogous discovery of three periods of sand drift on the plains of the Main near Darmstadt (Notizbl. Ver. Erdk. Darmstadt **1892**: 36–37).

[b] For examples see Boase—Trans. Roy. Geol. soc. Cornwall **2**: 142 (1822); Knowles—Jour. Anthrop. inst. **7**: 202 (1878), **9**: 320 (1879); C. W. Hall and Sardeson—Bull. Geol. soc. Amer. **10**: 352–359 (1899); Wahnschaffe—Ursachen der Oberflächengestaltung, p. 248 (1901); Shimek—Bull. Lab. nat. hist. Univ. Iowa **5**: 359 (1904); Coffey and Praeger—Proc. Roy. Irish acad. **25**: 193–196 (1904); etc.

[c] Proc. Inst. civ. eng. **150**: 380–381 (1902). Cf. the observations of Tenison-Woods on the South Australian coast—Jour. Proc. Roy. soc. N. S. Wales **16**: 60 (1882).

[d] If this fact is general it may have its application in the hypothesis of alternating changes of climate recently proposed by Huntington (The Pulse of Asia [1907]).

[e] See H. von Meyer—Neues Jahrb. Min. **1848**: 465–473; and Rice—Bull. U. S. Nat. mus. **25**: 15 (1884).

[f] For examples see Gregory—Quart. jour. Geol. soc. **17**: 480 (1861); Topley—Pop. sci. rev. **14**: 136 (1875); Reade—Geol. mag. (2) **8**: 197–198 (1881); Tenison-Woods—Jour. Proc. Roy. soc. N. S. Wales **16**: 61–62 (1882); Marsh—The earth as modified by human action, ed. of 1885, pp. 542, 551; Walther—Denudation in der Wüste, pp. 527–529 (1891); Doss—Korrespbl. Naturforscherver. Riga **39**: 32 (1896); Corstorphine—Ann. rept. Geol. comm. Cape Good Hope **2**: 25–28 (1897); Blake—Quart. jour. Geol. soc. **53**: 227–230 (1897); Rogers and Schwarz—Trans. South African phil. soc. **10**: 427–436 (1898); Evans—Quart. jour. Geol. soc. **56**: 559–581 (1900); Chapman—ibid. **56**: 584–589 (1900); Bishop—Amer. geol. **27**: 1–5 (1901); Bertololy—Kräuselungsmarken und Dünen, pp. 7–8 (1900); Philippi—Deut. Süd-polar Exped. **1**: 29 (1902); Dorsey et al.—Field Operations Bur. of Soils **1902**: 803; Braine—loc. cit.; and Branner—Amer. jour. sci. (4) **16**: 307 (1903). On the analogous phenomena of the consolidation of beach sands see the thorough discussion of Branner, in re the stone reefs of Brazil—Bull. Mus. comp. zool. **44**: 171–196 (1904).

sand are well developed in the Bahamas[a] and Bermudas,[b] on the coast of Florida,[c] on the Island of Fernando de Noronha,[d] etc.

These consolidated sands, whether the remains of coastal dunes or of those of the desert, are the only known strata which can be identified as eolian entirely from examination of their internal characteristics. However, with the advance of geologic science it has become increasingly possible to reconstruct from various lines of evidence the climatic conditions which prevailed in past geologic times and under which various strata were laid down. Geologists have thus been able in certain cases to reach the tentative conclusion that the strata concerned were terrestrially deposited and under conditions of more or less complete aridity,[e] which conditions must have been markedly favorable to eolian action, though direct trace of such action may not be preserved. Thus Goodchild[f] believes that the Old Red, or Devonian sandstone of England, was formed under desert or semidesert conditions; Passarge[g] thinks that the Mesozoic climate of all southern Africa was a dry one; Suess[h] advocates the hypothesis of terrestrial and arid origin for the Permian beds of the basin of Rossitz, Hungary; Matthew[i] and Loomis[j] believe that certain Tertiary beds of Nebraska represent an old deposit of desert loess; and Barrell[k] has ascribed a semiarid (though not desert) origin to the Mauch Chunk and similar formations in eastern Pennsylvania, which conclusion has been confirmed by

[a] Nelson—Quart. jour. Geol. soc. **9**: 200–215 (1853); A. Agassiz—Bull. Mus. comp. zool. **26**: 19, 46–47, 170 (1894); Shattuck—The Bahama Islands, pp. 12, 14–15 (1905).

[b] Nelson—Trans. Geol. soc. London (2) **5**: 103–123 (1840); Rein—Ber. senckenb. naturf. Ges. **1869–70**: 140, **1872–73**, 131; C. W. Thompson—The Atlantic, pp. 287–293 (1878); Rice—Bull. U. S. Nat. Mus. **25**: 9–15 (1884); A. Agassiz—Bull. Mus. comp.zool. **26**: 221–228 (1895); Verrill—Amer. jour. sci. (4) **9**: 313–340 (1900). The last article contains a bibliography.

[c] L. Agassiz—Bull. Mus. comp. zool. **1**: 373–375 (1869); Dall and Harris—U. S. Geol. surv. Bull. **84**: 101 (1892); A. Agassiz—Bull. Mus. comp. zool. **28**: 45 (1896).

[d] Branner—Amer. jour. sci. (3) **37**: 145–161 (1889), **39**: 247–257 (1890). Ridley, however, dissents from Branner's opinion as to the eolian origin of these rocks (ibid. (3) **41**: 406–409 [1891]).

[e] On the possibility of fossil deserts, see Walther—Rept. Brit. Assoc. **1896**: 795.

[f] Trans. Edinb. geol. soc. **7**: 203–222 (1897), Trans. Geol. soc. Glasgow **11**: 79 (1898), Proc. Geol. assoc. (2) **18**: 119 (1903). Goodchild's illustrative examples are criticised by Barron—Topography Sinai, Western Portion, p. 215 (1907).

[g] Zs. Ges. Erdk. Berlin **1904**: 176–193.

[h] Jahrb. geol. Reichsanst. **57**: 793–834, especially pp. 795–798 (1907). He also refers to several possibly similar localities elsewhere.

[i] Amer. Nat. **33**: 403–408 (1899).

[j] Amer. Jour. Sci. (4) **28**: 17 (1909).

[k] Bull. Geol. soc. Amer. **18**: 449–476 (1907). See also Grabau—Jour. geol. **17**: 209–250 (1909).

Wherry[a] on the ground of the occurrence therein of a mineral (carnotite) known to be formed under conditions of inadequate rainfall. Probably the best known and best established instances of such strata are those formed in the desert which seems to have existed over northern Europe in Triassic time.[b] In England especially dune sand has been found in the deposits,[c] wind corraded and polished surfaces[d] and surfaces showing insolational flaking[e] have been discovered under certain of the strata, faceted pebbles have been collected from them,[f] and other evidences of desert origin and eolian action brought to light.[g] The Keuper marls seem to represent the eolian loess deposited in the bordering areas.[h]

An important (though not the only) item in the evidence advanced in favor of the hypothesis of desert origin for certain of these strata is their red color, and it has been frequently urged that all red beds are desert, or at least subaerial, formations, it being claimed that the requisite oxidation of the iron could not otherwise be attained.[i] The incorrectness of this conclusion has been pointed out by Barrell.[j] Subaerial deposits are perhaps usually red, but this color is by no means an invariable indication of such a history. Even if the possi-

[a] In a paper before Section E, Amer. assoc. adv. sci., Baltimore, Md., Dec. 28, 1908. I am indebted to Dr. Wherry for a more extended summary of his views than was given at the meeting.

[b] Fraas—Jahresh. Ver. vaterl. Naturk. **55**: 42–58 (1899); Walther—Centbl. Min. **1904**: 5–12, Geschichte der Erde und des Lebens, pp. 366–384 (1908).

[c] Phillips—Quart. jour. Geol. soc. **37**: 13 (1881); Mackie—Trans. Edinburgh geol. soc. **7**: 166 (1897), Rept. Brit. Assoc. **1901**: 650; Lomas—ibid. **1903**: 655, Proc. Liverpool geol. soc. **10**: 194–196 (1905–6).

[d] Watts—Rep. Brit. Assoc. **1899**: 747, Geog. Jour. **21**: 632 (1903), Brit. assoc. Geol. photos. (3) No. **3755**, desc. p. 26; Mackie—Rept. Brit. assoc. **1901**: 650–651; Bosworth—Rept. Brit. Assoc. **1907**: 505–506, Trans. Leicester lit. phil. soc. **12**: 28–34 (1908).

[e] Lomas—loc. cit. p. 186.

[f] Beasley—Proc. Liverpool geol. soc. **10**: 87 (1905–6); Lomas—ibid. p. 196; W. D. Brown—ibid. pp. 128–131; Zimmermann—Monatsb. deut. geol. Ges. **1907**: 229–230.

[g] The evidence is summarized by Lomas—loc. cit. pp. 172–197; and Proc. Yorkshire geol. soc., n. s. **16**: 15–20 (1906). Bonney opposes the hypothesis of mainly desert origin (Quart. jour. Geol. soc. **56**: 288 [1900], **58**: 201 [1902], Proc. Yorkshire geol. soc., n. s. **16**: 1–14 [1906], Geol. mag. (5) **5**: 336–341 [1908]). See also Koken—Jahresh. Ver. vaterl. Naturk. **61**: lxxvi–lxxvii (1905); and Blanckenhorn—Monatsb. deut. geol. Ges. **1907**: 297–315.

[h] See Lomas—loc. cit.; Beasley—loc. cit. pp. 79–97; Bosworth—loc. cit.

[i] On the origin and meaning of red color in rocks and soils, see Crosby—Proc. Boston soc. nat. hist. **23**: 219–222 (1888), Amer. geol. **8**: 72–82 (1891); Russell—U. S. Geol. surv. Bull. **52**, 1889; Hudleston—Proc. Geol. assoc. (2) **11**: 104–144 (1889); Spring—Neues Jahrb. Min. **1899**, I: 47–62; Katzer—ibid. II: 177–181; Huntington—Bull. Geol. soc. Amer. **18**: 379–382 (1907); and especially the brief but excellent discussion by Barrell—Jour. geol. **16**: 285–293 (1908).

[j] Loc. cit. See also D. White—Jour. geol. **17**: 339–340 (1909).

bility of secondary (metamorphic) reddening[a] be rejected, it is still possible to imagine the red beds composed of material washed from an old and well weathered land surface and deposited in the surrounding seas.[b]

The problems of paleogeography are just beginning to be investigated. In recent years Bonney[c] has examined and discussed the evidences of past physiographic conditions which are furnished by certain breccias; Grabau[d] has pointed out the importance to the stratigrapher of a thorough study of the past history of strata in general; and Barrell,[e] in a most valuable paper, has analyzed the phenomena of erosion, deposition and stream transport and shown in what manner they are severally affected by variations in climatic conditions. The possibility of strata building under other than subaqueous conditions is a comparatively new concept. When it, and the various criteria by which previous climatic conditions may be traced (as outlined by Barrell), shall have become better known to, and understood by, field geologists, much progress may be expected in the identification of strata in the formation of which subaerial agencies in general, and the wind in particular, have been much more active than is now suspected.

VOLCANIC DUST AS SOIL MATERIAL.

FRAGMENTARY MATERIAL THROWN OUT BY VOLCANOES.

Besides gaseous matters and liquid lava, most erupting volcanoes eject much material in the solid form, consisting of fragments of rock, volcanic bombs, lapilli, and volcanic dust or "ash."[f] The amount of the fragmental material thus ejected by the more explosive eruptions is enormous. Junghuhn[g] estimated that 381 cubic kilometers (92 cubic miles) were ejected in the great eruption of Tomboro in Sumbawa in 1815, and even if we follow Verbeek[h] in reducing this amount to 150 cubic kilometers (36 cubic miles) it still remains stupendous. It is estimated that the material thrown out by the explosion of

[a] As suggested by Barrell—loc. cit.

[b] See Grabau's suggestions in re the red formations of New York (Science (n. s.) **22**: 528–535 [1905], Jour. geol. **17**: 245 [1909]).

[c] Quart. jour. Geol. soc. **58**: 185–206 (1902).

[d] Science (n. s.) **22**: 528–535 (1905). See also his article in Jour. geol. **17**: 209–250 (1909).

[e] Jour. geol. **16**: 159–190, 255–295, 363–384 (1908).

[f] For a discussion of all these classes of material see Johnston-Lavis—Proc. Geol. assoc. (2) **9**: 421–432 (1886).

[g] Java, vol. **2**, p. 819–828 (1854). On this eruption see also Landgrebe—Naturgeschichte der Vulcane, vol. **1**, pp. 262, 263 (1855).

[h] Krakatau, p. 141 (1885). This is the report to the Dutch Government on the eruption of Krakatoa and its accompanying phenomena.

Bandaisan in Japan in 1888 was about 2,000,000,000 tons.[a] Verbeek's[b] careful calculations of the material thrown out by the eruption of Krakatoa in the Straits of Sunda in 1883 lead to a value of 18 cubic kilometers (4.3 cubic miles), one-third of which fell at a distance of more than 15 kilometers (9.4 miles) from the seat of disturbance. The great eruptions of Papandayang[c] in Java in 1772, of Asama[d] in Japan in 1783, and of Skaptar Jökull[e] in Iceland in the same year doubtless produced even greater quantities of fragmental material than this. The eruption of Krakatoa was remarkable not for any great quantity of material discharged, but for the extreme violence of the explosions by which the discharge was effected. The quantity of material ejected by the recent (1902) eruptions of La Soufrière and Pelée in the West Indies was not insignificant.[f]

The above estimates are based on the thickness and area of deposits made near the volcanoes and hence include only the fragments of appreciable size and that part of the fine dust which was entangled by these large particles or carried down by local rains. A large part of the ejected material is fine enough to be carried long distances by the winds, and enough such volcanic dust has been, and is being, distributed by the atmosphere to render it worthy of attention as a constituent of the soil. It is estimated by Shaler[g] that not less than 300 cubic miles of fine dust has been discharged by the Javanese and Malayan volcanoes since 1770, and probably a more than equal quantity has been discharged by volcanoes in other parts of the earth during the same period.

CHARACTER AND PRODUCTION OF VOLCANIC DUST.

Volcanic dust has everywhere much the same appearance. Under th microscope it is seen to be made up of thin, irregular shaped fragments of vitreous material often so curved as to indicate that

[a] Sekiya and Kikuchi—Jour. Coll. sci. Imp. Univ. Japan **3**: 91–172 (1889).

[b] Krakatau—p. 140. On this eruption see also the report of the Royal Society of London cited in note *b*, p. 117. Both of these reports give full references to the literature. Many details of the eruption are also given in Proc. Roy. geog. soc., n. s. **6**: 142–152 (1884).

[c] Junghuhn—Java, vol. **2**, pp. 95–106 (1854). The discharged material is estimated at 29,343,000,000 cubic feet; Schneider—Jahrb. geol. Reichsanst. **35**: 1–26 (1885); Volz—Neues Jahrb. Min. Beilagebd. **20**: 123–132 (1905).

[d] Marshall—Trans. Asiatic Soc. Japan **6**: 328 (1878); Milne—Rept. Brit. Assoc. **1887**: 212–226.

[e] Thoroddsen—Ann. rept. Smithsonian Inst. **1885**: 495–541.

[f] Anderson and Flett—Proc. Roy. soc. **70**: 423–445 (1902); Hovey—Bull. Amer. mus. nat. hist. **16**: 333–372 (1902), Amer. jour. sci. (4) **14**: 319–358 (1902), Nat. geog. mag. **13**: 444–459 (1902), papers by Hill, Russell, Diller, Hillebrand, and Page in the last-named journal, **13**: 223–301, 415–436 (1902); Heilprin—Eruption of Pelée, 1908.

[g] Ann. Rept. U. S. Geol. Surv. **12**, I: 240–241 (1891).

they once formed parts of the walls of bubbles of glass.[a] The fragments themselves frequently contain small cavities, evidently bubbles which remained unbroken. Complete hollow spheres of glassy material have also been found.[b] Ordinary porous pumice when pulverized gives a dust of this sort, and it is probable that some volcanic dust originates by the mutual attrition of fragments of pumice rising and falling above the crater.[c] It seems, however, to be more largely formed by the blowing apart of the lava itself by steam (or water) occluded in its mass and suddenly released from pressure when the eruption takes place.[d]

The crystals of various minerals which are found mixed with the glassy material of volcanic dust are probably in part microlites which had crystallized out of the still fluid magma before the explosion and in part fragments detached by attrition from pieces of previously solidified rock hurled into the air. It is possible, as suggested by Abbe[e] that some of the finest dust of volcanic origin may be derived from the evaporation in the air of droplets of water highly charged with soluble substances.

The quantity of dust produced by any particular eruption depends in the main on the violence of the explosion; that is, the amount of confined steam and the suddenness with which it is released. If the volcanic magma has sufficiently free access to the air the pressure will be relieved gradually and lava will flow out slowly with little or no explosive activity and the production of practically no dust. Nearly all eruptions are, however, partly explosive in character, and hence lead to the production of more or less dust.

THE AIR-TRANSPORT OF VOLCANIC DUST.

On account of the irregular form and common vesicular structure of its component fragments, volcanic dust is very easily lifted and

[a] On the characteristics of volcanic dust see Zirkel—Neues Jahrb. Min. **1872**: 24; Murray and Renard—Proc. Roy. soc. Edinburgh **12**: 477–488 (1883–84). Also the various references to occurrences of volcanic dust cited on pp. 149–151 below. Barbour's paper cited on p. 151 contains a number of figures showing the microscopic appearance of various volcanic dusts. Figures are also given by Beijerinck—Nature **29**: 308–309 (1884); Diller—ibid. **30**: 91–93 (1884), Science **3**: 651–654 (1884); and Judd—Roy. soc. Rept. on Krakatoa, plates 3 and 4 (1888).

[b] Humboldt—Kosmos, vol. 4, p. 255 (1858).

[c] Judd—Roy. soc. Rept. on Krakatoa, p. 39 (1888).

[d] Penck—Zs. deut. geol. Ges. **30**: 97–129 (1878), especially pp. 127–128; Hixon—Min. and sci. press **95**: 809 (1907). Murray and Renard (Proc. Roy. soc. Edinburgh **12**: 480 [1883–84],) suggest that the dust may be formed by the explosion of droplets under tension caused by cooling—analogous to the phenomena of "Prince Rupert's drops." See also Forel—Bull. Soc. vaud. sci. nat. (4) **39**: xxxiv–xxxv (1903). It seems doubtful if such a cause is competent to account for the enormous quantities of dust produced.

[e] Mon. weath. rev. **34**: 164 (1906).

sustained by the wind,[a] and it is also raised to great heights by the volcanic explosions themselves, by ascending currents of steam and heated air, and by the whirlwinds often formed over the crater.[b] Therefore, although it of course falls in greater quantity near the point of origin, it is by no means confined to that locality, but may be, and is, carried to great distances by the wind. Volcanic dust from Iceland has several times fallen in Scandinavia,[c] in northern Great Britain,[d] and in Holland.[e] Dust from Tomboro fell on Sumatra a thousand miles away.[f] Krakatoa ashes fell inches deep at distances of nearly 1,000 miles from the volcano,[g] and small quantities fell even in Holland.[h] Dust from Colima in Mexico fell in February and March, 1903, at points over 200 miles north and east of the volcano,[i] and the ash from Santa María in Guatemala in October, 1902, covered all the northern part of that country and most of the states of Tabasco, Veracruz, and Oaxaca in southern Mexico.[j] At Tapachula, 40 miles away, the ashes were 19.5 centimeters thick.[k]

Ash from Coseguina in Nicaragua in 1835 covered an area of 1,500,000 square miles[l] and even reached Jamaica, more than 750 miles away.[m] The dust from the eruption of Cotopaxi in Equador in 1877 fell at Guayaquil, 150 miles away, to the amount of 315 kilograms on every square kilometer during the first thirty hours of the fall. Once 209 kilograms fell in twelve hours.[n] The dust

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[a] Murray and Renard—Proc. Roy. soc. Edinburgh **12**: 486 (1883–4.)

[b] See p. 87.

[c] Zirkel—Neues Jahrb. Min. **1875**: 399; Daubrée—Compt. rend. **80**: 994, 1059 (1875); N. A. E. Nordenskiöld—Geol. mag. (2) **3**: 292–297 (1876), Met. Zs. **11**: 201–206 (1894). On May 3, 1892, the dust amounted to between 1 and 2 grams per square meter.

[d] Daubrée—loc. cit.; Geikie—Textbook of geology, 4th ed., vol. **1**, p. 295 (1903).

[e] Vom Rath—Monatsb. K. Preuss. Akad. Wiss. Berlin **1875**: 282–286.

[f] Élie de Beaumont—Leçons de géologie pratique, vol. **1**, p. 188 (1847).

[g] See the Royal society report already cited (on p. 117) and Verbeek's work also cited (on p. 146). Also Judd—Nature **29**: 152, 595 (1883–1884), and the symposium—ibid., pp. 174–175 (1883).

[h] Beijerinck and van Dam—Nature **29**: 175 (1883).

[i] Ordóñez—Rev. Soc. cient. Antonio Alzate **20**: 99–104 (1903). On this volcano and its eruptions see also Kerber—Verh. Ges. Erdk. Berlin **9**: 237–246 (1882); Sperry—Amer. jour. sci. (4) **15**: 487–488 (1903); H. Köhler—Prometheus **17**: 214–219 (1906).

[j] On this eruption see Sapper—Centbl. Min. **1903**: 33–44, 65–72; Schmidt—ibid., p. 131; Brauns—ibid., p. 132, 290; Eisen—Bull. Amer. geog. soc. **35**: 325–352 (1903); and Ordóñez—Par. Inst. geol. Méx. **1**: 229–234 (1904). Eisen's figure for the dust-covered areas is too large (Böse—Par. Inst. geol. Méx. **1**: 51–54 [1904]).

[k] Brauns—loci citati.

[l] Tissandier—Rev. sci. (2) **18**: 815 (1880).

[m] Élie de Beaumont—Leçons de géologie pratique, vol. **1**, p. 188 (1847); Schiefer—Wetter **20**: 258 (1903).

[n] Wolf—Neues Jahrb. Min. **1878**: 141. The eruption is described by Whymper—Travels amongst the Great Andes, 1892.

ejected by this same volcano in 1888 amounted to more than 2,000,000 tons.[a] On this occasion the dust cloud traveled 85 miles in six hours.[b] At the eruption of Tarawera in New Zealand in 1886, 1,960,000,000 cubic yards of dust was discharged in five or six hours and covered a land area of over 6,000 square miles.[c] Much more dust fell into the sea. Dust from the eruptions of La Soufrière and Pelée in 1902 fell plentifully all over the West Indies and especially at Barbados,[d] 130 miles from Pelée and 225 from La Soufrière. Dust from the eruption of Pelée in 1812 is said to have reached the Azores.[e] Dust from Vesuvius has been observed in Greece,[f] in France,[g] and in Austria.[h]

All these observations refer to falls of dust in such quantity that it could be collected or easily observed. From the optical effects of such material in the atmosphere it is known that small amounts of volcanic dust are transported to very much greater distances.[i] At the time of the Krakatoa eruption dust was distributed over nearly the whole earth.

From the ease of transfer of volcanic dust and the large number of volcanoes discharging it,[j] it follows that the soil in all parts of the earth is likely to receive at least some slight accretion from this source. The accretion is of course largest in countries of many volcanoes, such as Japan, Java, and Central America, and in the neighborhood of isolated active volcanoes like Vesuvius and Etna. In these localities volcanic dust is always an important, and often the most important, constituent of the soil materials. Even, however, in countries far from active volcanoes the share of volcanic dust in

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[a] Whymper—loc. cit. p. 328.

[b] Whymper—Nature **29**: 199 (1883).

[c] Cadell—Trans. Edinb. geol. soc. **7**: 183–200 (1896).

[d] 2,200,000 tons fell on Barbados on May 7–8 (Häpke—Abh. naturw. Ver. Bremen **17**: 545 [1903]). See also Diller and Steiger—Science (n. s.) **15**: 947–950 (1902); Morris—Quart. jour. Geol. soc. **58**: lxxxiv (1902); Porter—Nature **66**: 131 (1902); Bonney—Nature **67**: 584 (1903); Häpke—Himmel und Erde **15**: 89–92 (1902); Barenborg and Gottsche—Annalen Hydrog. **31**: 270–271 (1903); and the references cited on p. 147. For a notice of fall of Pelée dust at San Juan, Porto Rico, 400 miles away, see Thompson—Mon. weath. rev. **30**: 488 (1902). Dust from these eruptions fell on ships as much as 600 miles away (Page—Nat. geog. mag. **13**: 299–301 [1902]).

[e] Porter—Nature **66**: 132 (1902).

[f] Élie de Beaumont—Leçons de géologie pratique, vol. **1**, p. 188 (1847).

[g] Meunier—Compt. rend. **142**: 938 (1906); van den Broeck—Ciel et terre **27**: 330–334 (1906).

[h] Ohnesorge—Verh. geol. Reichsanst. **1906**: 296–297; Veenema—Wetter **23**: 116–117 (1906); and notices by von Nettovich, Mazelle, and Janežič—Met. Zs. **23**: 223–225 (1906).

[i] See Archenhold—Weltall **2**: 225–227 (1902); Stentzel—Wetter **21**: 121–125 (1904).

[j] Probably about 300 or 400 (A. Geikie—Textbook of geology, 4th ed., p. 346 [1903]). Milne thinks that the volcanoes active in the past 4,000 years would number several thousand (Earthquakes and other earth movements, p. 227 [1886]).

soil formation is not always negligible.[a] The ubiquity of volcanic dust is shown by its constant presence in deep-sea deposits.[b]

VOLCANIC TUFFS.

But the volcanic material of importance to the soil is not alone that furnished by contemporaneous eruptions. There exist in practically all parts of the earth beds of volcanic ash or "tuff" derived from the volcanoes of previous geologic time.[c] Some of these tuffs are as fresh and unconsolidated as if they had been deposited yesterday. Many show traces of deposition by water and probably consist of material which fell into lakes and rivers. Others were evidently deposited by the wind alone. Deposits of tuff are common over most of the United States west of the Mississippi and north of (but including) Colorado and Utah, and exist in a few other of the Western States.[d] Similar deposits occur in Alaska.[e]

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[a] Cf. A. Geikie—Textbook of geology, 4th ed., p. 295 (1903).

[b] Murray—Proc. Roy. soc. Edinburgh **9**: 247–262 (1876); Murray and Renard—Nature **29**: 588 (1884); Walther—Einleitung in der Geologie als historische Wissenschaft, p. 955 (1894); Shaler—Bull. Geol. soc. Amer. **7**: 490–492 (1896).

[c] On tuffs in general see Reyer—Jahrb. geol. Reichsanst. **31**: 57–66 (1881); Penck—Zs. deut. geol. Ges. **31**: 504–577 (1879); A. Geikie—Textbook of geology, 4th ed., pp. 172–175 (1903), and references cited by these authors.

[d] On the unconsolidated tuffs or beds of volcanic ash in the western United States see the following authors: Dutton—High plateaus of Utah, pp. 71–74, 192 (1880); Aughey—Sketches of the physical geography and geology of Nebraska, pp. 238–241 (1880); Garman—Boston Transcript, Nov. 10, 1882 (also notice of this same occurrence in Wadsworth—Mem. Mus. comp. zool. **11**: 17 [1884], and Science **6**: 63 [1885]); Merrill—Science **5**: 335 (1885) (more fully in Proc. U. S. Nat. mus. **8**: 99–100 [1886]). See also Merrill—Rocks, rock-weathering and soils, p. 337 (1906); Russell—U. S. Geol. surv. Monogr. **11**: 146–149 (1886); Peale—Science **8**: 163–165 (1886), U. S. Geol. surv. Geol. folio **24**, 1896; Todd—Science **7**: 373 (1886); Hicks—Amer. geol. **1**: 277–280 (1888), **2**: 64, (1888); Turner—Bull. Phil. soc. Wash. **11**: 389 (1891); Dumble—Trans. Tex. acad. sci. **1**: 33–34 (1892); Udden—Amer. geol. **11**: 268–271 (1893), Pop. sci. mon. **54**: 222–229 (1898); Barbour—Proc. Nebraska acad. sci. **1894–95**: 12–17; Turner—Science (n. s.) **1**: 453–455 (1895); Montgomery—ibid., pp. 656–657; Dumble—ibid. **5**: 657–658; Cross—U. S. Geol. surv. Monogr. **27**: 311–315 (1896); Salisbury—Science (n. s.) **4**: 816–817 (1896); Cragin—Colo. Coll. studies **6**: 53–54 (1896); Winchell and Grant—Amer. geol. **18**: 211–213 (1896); Todd—Science (n. s.) **5**: 62 (1897); Barbour—Mineral ind. **1897**: 22–25; Haworth—Univ. Geol. surv. Kansas **2**: 256–257 (1897), U. S. Geol. surv. Water sup. pap. **6**: 33 (1897); Darton—Ann. rept. U. S. Geol. surv. **19**, IV.: 760–761 (1899); Berkey—Amer. geol, **21**: 146–147 (1898); Russell—U. S. Geol. surv. Water sup. pap. **53**: 32–34 (1901), ibid., Bull. **199**: 50, 73 (1902), Bull. **217**: 61 (1903); Spurr—ibid., Bull. **208**: 65 (1903); Rowe—Univ. Montana Bull. **17**, 1903; Woolsey—U. S. Geol. surv. Bull. **285**: 476–479 (1906); W. T. Lee—ibid. **352**: 84 (1908). Samples are described by Diller—U. S. Geol. surv. Bull. **150**: 212–214, 245–248 (1898); and by Iddings—ibid., pp. 146–148. For references to American occurrences of altered and consolidated tuffs see p. 152 below.

[e] Schwatka—Along Alaska's great river, p. 196 (1885); Dawson—Ann. rept. Geol. and nat. hist. surv. Canada **3**, I: 43B–46B (1887–8); Russell—Bull. Geol. soc. Amer. **1**: 145 (1890); Hayes—Nat. geog. mag. **4**: 146 (1892); Spurr—Ann. rept. U. S. Geol. surv. **18**, III: 223 (1898); Brooks—Ann. rept. U. S. Geol. surv. **21**, II: 365–366 (1900).

Deposits of volcanic ash which have been more or less altered and indurated are also common in many parts of the world. In North America they have been found in Maine,[a] Massachusetts,[b] Connecticut, and other New England States;[c] in Michigan,[d] Montana,[e] Colorado,[f] Wyoming,[g] and California;[h] in Canada,[i] in the West Indian Islands,[j] and in the neighborhood of the Mexican volcanoes. It is probable that deposits as yet undescribed occur in many other localities.

THE COMPOSITION OF VOLCANIC DUSTS.

The composition of volcanic dusts depends of course upon that of the lavas from which they are derived. The glassy material—always by far the larger part[k]—is simply undifferentiated lava, acid or basic, as the case may be. An analysis of the glassy part of the dust from the Krakatoa eruption is given as No. 9 in Table IX, page 155. The minerals found in determinable size are mainly plagioclase feldspars, rhombic and monoclinic pyroxenes (augite and hypersthene) and magnetite.[l] Hornblende and olivine are less frequent but not

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[a] H. E. Gregory—U. S. Geol. surv. Bull. **165**: 119–131 (1900).

[b] E. Hitchcock—Geology of Massachusetts, p. 648 (1841); Diller—Proc. Boston soc. nat. hist. **20**: 355–368 (1881).

[c] E. Hitchcock—Amer. jour. sci. (2) **4**: 199–207 (1847); Emerson—Bull. Geol. soc. Amer. **8**: 59–86 (1897).

[d] G. H. Williams—U. S. Geol. surv. Bull. **62**: 151–154, 158–159, 175–177 (1890).

[e] Merrill—Amer. jour. sci. (3) **32**: 199–204 (1886).

[f] Cross—Ann. rept. U. S. Geol. surv. **16**, II: 50–53, 60–63 (1895).

[g] Sinclair—Bull. Amer. mus. nat. hist. **22**: 273–280 (1906), **26**: 25–27 (1909).

[h] Turner—Ann. rept. U. S. Geol. surv. **17**, I: 627 (1896); Diller—U. S. Geol. surv. Bull. **150**: 211–213 (1898).

[i] In the Sudbury region: Barlow—Can. Geol. surv. Summ. rept. **1902**: 256–257. In the Lake of the Woods region: Lawson—Geol. and nat. hist. surv. Canada Ann. rept. (n. s.) **1**, Rept. CC: 51 (1886). In British Columbia: Ferrier—Canada Geol. surv. (n. s.) **7**, Rept. B, App. 1: 355–356, 358–359, 364–368 (1896).

[j] Spencer—Quart. jour. Geol. soc. **58**: 345, 347, 349, 351–353 (1902). On the recent tuffs of St. Vincent see Howe—Amer. jour. sci. (4) **16**: 317–322 (1903).

[k] The Krakatoa dust was about 91 per cent glass, 6 per cent feldspar, 1.3 per cent hypersthene, 0.6 per cent augite, and 1 per cent magnetite (Verbeek—Krakatau, p. 312 [1886]).

[l] For mineralogical examinations of volcanic dusts see the following papers:

On dust from Vesuvius, February 9, 1850: Ehrenberg—Ber. K. preuss. Akad. Wiss Berlin **1850**: 78–79. From the same volcano, April 27–28, 1872: Früh—Met. Zs. **20**: 175 (1903).

On the dust of the Swedish fall of May 3, 1892: Ussing—Vidensk. medd. Naturh. fören. Copenhagen **44**: 131–138 (1892); Nordenskiöld—Met. Zs. **11**: 205–206 (1894).

On the dust from Krakatoa: Verbeek—Krakatau, pp. 221–302 (1885); Murray and Renard—Proc. Roy. soc. Edinburgh **12**: 479–488 (1883–84); Renard—Bull. Acad. roy. Belg. (3) **6**: 495–506 (1883); Daubrée—Compt. rend. **97**: 1104 (1883); Joly—Sci. proc. Roy. Dublin soc. (n. s.) **4**: 291–299 (1884).

On dust from La Soufrière and Pelée in 1902: Anderson and Flett—Proc. Roy. soc. **70**: 430 (1902); Flett—Quart. jour. Geol. soc. **58**: 368 (1902); Bonney—ibid. Proc.:

uncommon. Micas have been found in Vesuvius dust,[a] in the Swedish dust of May, 1892,[b] in that of Pelée[c] and of Santa María,[d] and possibly in that from Krakatoa.[e] The materials from Vesuvius[f] and from Pelée[c] also contain leucite. Pyrite has been found in Krakatoa dust[g] and in dust which fell at Dominica, West Indies, on January 4, 1880.[h] This latter dust also contained galena, which, as perhaps also the pyrite, may have been secondary, and formed by reactions occurring after the eruption. Zircons were found in the Swedish dust,[b] in that from Santa María,[i] and probably in that from Pelée.[j] Apatite was present in the dust from Krakatoa,[k] Pelée,[j] and Santa María.[l] In all examinations of volcanic dust it is of course necessary to guard against the very possible admixture of local soil material transiently suspended in the atmosphere. The beds of prehistoric volcanic ash have of course practically the same mineralogical composition as their modern analogues.[m]

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lxxxvi (1902); Klein—Sitzungsb. K. preuss. Akad. Wiss. Berlin **1902**: 993–994; Porter—Nature **66**: 131–132 (1902); Falconer—ibid. p. 132; Gentil—Bull. Soc. géol. France (4) **2**: 320–321 (1902); Levy—Compt. rend. **134**: 1123–1124 (1902); Diller and Steiger—Science (n. s.) **15**: 947 (1902); Diller—Nat. geog. mag. **13**: 289–294 (1902); Lacroix—Compt. rend. **134**: 1327–1329 (1902); Albuquerque and Smith—West Indian bull. **4**: 97–100 (1903); Barenborg and Gottsche—Annalen Hydrog. **31**: 271 (1903); Häpke—Abh. naturw. Ver. Bremen **17**: 545 (1903).

On dust from Santa María, Guatemala, in 1901: Ordóñez—Rev. Soc. cient. Antonio Alzate **18**: 34–35 (1902), Par. Inst. geol. México **1**: 231 (1904); Bergeat—Centbl. Min. **1903**: 112–117; Schmidt—ibid., p. 131; Brauns—ibid., pp. 132–134; Schottler—ibid., pp. 288–289. For a qualitative chemical analysis see: Villa-señor—Boll. Sec. Fomento México (2) 2, **7**, II: 279–280 (1902).

On dust from Colima, Mexico, in 1903: Ordóñez—Mem. Rev. Soc. cient. Antonio Alzate Rev. **20**: 103 (1903).

On several samples from Cotopaxi: Bonney—Proc. Roy. soc. **37**: 122–125 (1884). See also Nature **16**: 335 (1877).

[a] Ehrenberg—Ber. K. preuss. Akad. Wiss. Berlin **1850**: 79.

[b] Nordenskiöld—Met. Zs. **11**: 205–206 (1894).

[c] Häpke—Abh. naturw. Ver. Bremen **17**: 545 (1903).

[d] Schmidt—Centbl. Min. **1903**: 131; Brauns—ibid., pp. 132–134; Schottler—ibid., pp. 288–289.

[e] Murray and Renard—Nature **29**: 587 (1884).

[f] Früh—Met. Zs. **20**: 175 (1903).

[g] Murray and Renard—Nature **29**: 587 (1884); Daubrée—Compt. rend. **97**: 1104 (1883); Verbeek—Krakatau, pp. 293–295 (1885).

[h] Daubrée—Compt. rend. **90**: 624–626 (1880).

[i] Brauns—Centbl. Min. **1903**: 132–134; Schottler—ibid., pp. 288–289.

[j] Flett—Quart. jour. Geol. soc. **58**: 368 (1902).

[k] Murray and Renard—Nature, **29**: 587 (1884); Verbeek—Krakatau, p. 292 (1885).

[l] Ordóñez—Mem. Rev. Soc. cient. Antonio Alzate Rev. **18**: 34 (1902), Par. Inst. geol. Méx. **1**: 231 (1904); Brauns—Centbl. Min. **1903**: 132–134; Schottler—ibid., pp. 288–289.

[m] Mineralogical examinations of samples from Montana are given by Clarke and Hillebrand—U. S. Geol. surv. Bull. **148**: 197 (1897); and by Iddings—ibid., Bull. **150**: 147 (1898).

The chemical compositions of various volcanic dusts and tuffs are given in Tables IX, X, and XI, the analyses being numbered continuously throughout the three tables. Analyses 1 and 2 were made by Dufrénoy[a] of dusts from the two Central American volcanoes named. Nos. 3, 4, and 5 are of dusts discharged by the eruption of Krakatoa, No. 3 being of dust which fell in the immediate vicinity of the volcano, No. 4[b] of that which fell at Buitenzorg, 100 miles away, and No. 5[c] of that which fell on board the steamer *Barbarossa*, in latitude 10° 41′ south and longitude 93° 15′ east of Greenwich, about 900 miles ENE. of Krakatoa. No. 6[d] is a dust which fell on the deck of a ship in the harbor of St. Pierre, Martinique, during the eruption of Mount Pelée in 1902, and No. 7[e] is of dust which fell at Barbados during the eruptions of La Soufrière in the same year. No. 8[f] is of volcanic sand from the recent (though not historic) eruption at the Cinder Cone in the Lassen Peak district, California. No. 9[g] is of the glassy part of the Krakatoa dust which fell at Buitenzorg, the complete analysis of which is given as No. 4.

All the analyses in Table X are of the loose volcanic ash deposits of the western States, described on page 151. The references to authorities are given in the notes to the table. Table XI contains a few analyses of tuffs which have undergone metamorphism and been consolidated into more or less compact rock. In Nos. 20, 21, 22, and 24 the process has been silicification. In No. 23 the cement is evidently calcareous.[h]

All the analyses (except No. 23, which contains $CaCO_3$ as just noted) are expressed in percentages of the ignited weight. This

[a] Ann. mines (3) **12**: 355–372 (1837), Compt. rend. **6**: 177 (1838).

[b] Analysis by Winkler, quoted by Verbeek—Krakatau, p. 305 (1886).

[c] Oebbeke—Neues Jahrb. Min. **1884**: II, 32–33 (cited by Verbeek—Krakatau, p. 323 [1886]). For other analyses of Krakatoa dust (which agree fairly well with those quoted) see Judd—Roy. soc. Rept. on Krakatoa, p. 40 (1888); Verbeek—Krakatau, pp. 305–314 (1886); Sauer—Sitzungsb. naturf. Ges. Leipzig **10**: 87 (1883); Murray and Renard—Proc. Roy. soc. Edinburgh **12**: 484 (1883–84); van der Burg—Rec. trav. chim. Pays Bas **2**: 298–303 (1883). For criticisms of the two last analyses see Verbeek—Krakatau, pp. 317 and 319, respectively.

[d] Chem. news **85**: 282 (1902). For other analyses of Pelée dust see Lacroix (analyses by Pisani)—Compt. rend. **134**: 1329 (1902); Carmody—Trinidad Mirror, May 22, 1902; Wiechmann—Science (n. s.) **15**: 910–911 (1902); Steiger—ibid., p. 948; Hovey (analysis by Hillebrand)—Amer. jour. sci. (4) **14**: 327 (1902); Diller—Nat. geol. mag. **13**: 291 (1902); Griffiths—Chem. news **88**: 231 (1903); Schmelck—Chemztg. **27**: 34 (1903). The dust from the eruption of 1851 as analyzed by Pisani (Lacroix, loc. cit.) is not essentially different from that of 1902.

[e] Analysis by Pollard, quoted by Flett—Quart. jour. Geol. soc. **58**: 369 (1902), and Teall—Nature **66**: 130 (1902). Another analysis by Hillebrand is quoted by Rowe—Univ. of Montana Bull. **17**: 10 (1903). See also Diller—Nat. geol. mag. **13**: 291 (1902). A dust from the eruption of the Grand Soufrière at Dominica in 1880 has been analyzed by Daubrée—Compt. rend. **90**: 625 (1880).

[f] Hillebrand, quoted by Diller—U. S. Geol. surv. Bull. **79**: 29 (1891). Also given in Bull. **148**: 198 (1897).

[g] Verbeek—Krakatau, p. 311.

[h] This sample contained 13.81 per cent of carbon dioxide.

makes all comparable and the errors introduced are small since material of this sort loses on ignition practically nothing but its hygroscopic water. Some of the analyses have been recalculated to bring them to this basis.

TABLE IX.—*Chemical analyses of volcanic dusts.*

Constituents.	Volcano.								
			Krakatoa.						
	Cosiguina, Nicaragua.	La Soufrière, Guadeloupe.	Dust fallen at Krakatoa.	Dust fallen at Buitenzorg.	Dust fallen on ship 900 miles away.	Pelée: Dust fallen at Barbados.	La Soufrière: Dust fallen at Barbados.	Volcanic sand from Lassen Peak, California.	Glassy part of Krakatoa dust: Buitenzorg.
	1	2	3	4	5	6	7	8	9
SiO_2	61.45	59.10	61.36	66.26	69.52	53.40	53.02	56.01	68.12
Al_2O_3	19.63	22.54	17.77	16.31	15.37	21.00	18.85	17.40	15.81
Fe_2O_3	.....	2.58	4.39	3.38	0.29	9.50	3.29	1.50	5.01
FeO	2.30	.....	1.71	1.36	3.74	.....	4.60	5.21	
CaO	3.10	5.10	3.45	3.61	2.77	9.70	9.62	8.06	2.78
MgO	0.61	1.42	2.32	1.06	0.83	2.00	5.21	7.31	1.18
K_2O	2.77	4.38	2.51	2.23	3.48	0.85	0.60	1.35	1.06
Na_2O	8.87	2.27	4.98	4.45	4.35	2.33	3.24	3.33	5.09
P_2O_5	.....	.....	.....	.....	.....	0.25	.....	.....	.....

NOTE.—For references to the authorities for the above analyses see p. 154.

TABLE X.—*Chemical analyses of unconsolidated volcanic tuffs.*

Constituents.	Harlan County, Nebr.	Fort Ellis, Mont.	Bozeman, Mont.	Little Sage Creek, Mont.	Gallatin Valley, Mont.	Ravalli County, Mont.	Marsh Creek Valley, Idaho.	Cottonwood Canyon, Idaho.	Truckee River, Nev.	Owens Lake, Cal.
	10.[a]	11.[b]	12.[c]	13.[d]	14.[e]	15.[f]	16.[g]	17.[h]	18.[i]	19.[j]
SiO_2	72.05	69.24	75.83	71.05	74.65	69.95	74.55	71.50	74.00	57.65
Al_2O_3	18.40	24.62	16.20	19.76	13.79	21.80	17.56	14.89	16.61	11.04
Fe_2O_3					1.24			1.21		3.54
FeO					1.27			1.28		.69
CaO	.90	2.08	1.27	2.80	1.21	.....	1.75	2.21	.89	9.45
MgO	.25	1.51	.36	.78	1.24	.40	Trace.	.49	.43	2.29
K_2O	6.92	1.40	3.17	4.27	6.07	4.26	4.33	2.68	3.50	3.08
Na_2O	1.68	.91	2.96	2.26	1.34	4.58	1.69	5.28	5.14	3.19
P_2O_5	.....	.....	.....	.....	.....	.....	.....	.10	.....	.28

[a] Merrill—Rocks, rock-weathering, and soils, 2d ed., p. 338 (1906). An analysis of tuff from Bazile Creek, Nebraska, is given by Clarke—U. S. Geol. surv. Bull. 42: 142 (1887). An analysis by Nicholson of an average sample of Nebraska tuff is given by Barbour—Proc. Nebraska acad. sci. 1894-95: 13.

[b] Clarke—U. S. Geol. surv. Bull. 42: 141 (1887). Also in Bull. 148: 141 (1897).

[c] Clarke—U. S. Geol. surv. Bull. 42: 141 (1887). Also in Bull. 148: 141 (1897). The analysis of a second sample from the same locality is also given, as well as that of a sample from Devil's Pathway, Montana, and one from Dry Creek Valley, Montana.

[d] Loci citati in last note; also Merrill—Rocks, rock-weathering, and soils, 2d ed., p. 133 (1906).

[e] Stokes—U. S. Geol. surv. Bull. 148: 141 (1897).

[f] Rowe—Univ. of Montana Bull. 17: 9 (1903). An analysis of a second sample from the same locality is also given.

[g] Loci citati in notes *c* and *d*.

[h] Hillebrand—U. S. Geol. surv. Water supp. pap. 53: 34 (1901).

[i] Chatard—U. S. Geol. surv. Bull. 9: 14 (1884). Also given by Russell—U. S. Geol. surv. Monogr. 11: 147 (1886).

[j] Chatard—U. S. Geol. surv. Bull. 148: 229 (1897). An analysis of a sample from near Redding, Cal., is also given. Analyses by Steiger of two samples from the Downieville area, California, are given in the Ann. rept. U. S. Geol. surv. 17, I: 627 (1895-96). An acid digestion analysis by Colby of a sample from Placerville, Cal., is given by Loughridge—Cal. agr. expt. stat. Rept. 1898-1901, II: 173. An analysis by Stokes of an impure tuff, partly of organic origin, from Douglas County, Oreg., is given by Clarke—U. S. Geol. surv. Bull. 168: 223 (1900). Eight analyses of recent tuffs from the Hawaiian Islands are reported by Maxwell—Lavas and soils of the Hawaiian Islands, Spec. Bull. A, Hawaiian sugar planters' expt. stat., p. 21 (1898). Analyses of four samples from the Philippine Islands are reported by Cox—Philip. jour. sci. 3: 404 (1908).

TABLE XI.—*Chemical analyses of metamorphosed tuffs.*

	Oldberg, Odenwald, Germany.	Chemnitz, Germany.	St. David's, Wales.	Castle Hill, Me.	Marquette, Mich.
	20.[a]	21.[b]	22.[c]	23.[d]	24.[e]
SiO_2	83.30	77.52	82.18	83.40	75.78
Al_2O_3	9.65	14.18	11.51	12.29	13.54
Fe_2O_3	.43	3.23	.29	2.52	.46
FeO	.58		1.44	7.95	.79
CaO	.54		.53	17.77	.32
MgO	Trace.		.97	5.65	1.15
K_2O	4.74	4.46	3.04	.79	3.74
Na_2O	.59	1.09	.73	2.40	.57
P_2O_5				.49	Trace.

[a] E. Cohen—Die zur Dyas gehörigen Gesteine des südlichen Odenwaldes, p. 57 (1871).
[b] Eras—Neues Jahrb. Min. 1864: 673-686. An analysis of similar material from the same locality is given by Knop in the same Jahrbuch, 1859: 575. Both are quoted by G. H. Williams—U. S. Geol. surv. Bull. 63: 153. An analysis of a similar tuff from Triberg in the Black Forest is given by G. H. Williams—Neues Jahrb. Min. Beilagebd. 2: 630 (1883).
[c] A. Geikie—Quart. jour. Geol. soc. 39: 297 (1883).
[d] Hillebrand, quoted by Gregory—U. S. Geol. surv. Bull. 165: 184 (1900). Also quoted by Clarke—Ibid., Bull. 168: 20 (1900).
[e] Hillebrand, quoted by G. H. Williams—U. S. Geol. surv. Bull. 63: 152 (1890).

From the point of view of the influence of this material on the soil, the most interesting thing about the analyses is the considerable content of potassium which they show. Among the volcanic dusts only those of Pelée and La Soufrière show less than 1 per cent of K_2O, and the tuffs of Table X are still higher. In addition to the values given in the tables, other analyses of Krakatoa dust have given K_2O percentages[a] of 1.00,[b] 1.06,[c] 1.46,[d] 1.82,[e] 2.25,[f] and 2.46.[g] Van der Burg[g] obtained a value of only 0.155 per cent, but this is so much below all other determinations as to be seriously in doubt, especially as his analyses have been questioned on other grounds.[h] In the West Indian dusts of 1902 Hillebrand[i] found 0.67 per cent K_2O; Steiger[j] found 0.72 per cent; Griffiths[k] found 0.65 per cent; Pisani[l] found 0.89 per cent; and Schmelck[m] found 0.96 per cent and 0.55 per cent. The dust from the eruption of this volcano in 1851 contained 1.66 per cent K_2O.[n] Dust (probably volcanic) which fell

[a] All percentages are figured to the ignited weight as in the tables.
[b] Murray and Renard—Nature 29: 588 (1884).
[c] Verbeek—Krakatau, p. 311 (1886).
[d] Sauer—Sitzungsb. naturf. Ges. Leipzig 10: 87 (1883).
[e] Verbeek—Krakatau, p. 305 (1886).
[f] Judd—Roy. soc. Rept. on Krakatoa, p. 40 (1888).
[g] Rec. trav. chim. Pays-Bas 2: 298-303 (1883).
[h] Verbeek—Krakatau, p. 319 (1886).
[i] Hovey—Amer. jour. sci. (4) 14: 327 (1902).
[j] Science (n. s.) 15: 948 (1902). See also Diller—Nat. geog. mag. 13: 291 (1902).
[k] Chem. news 88: 231 (1903).
[l] Quoted by Lacroix—Compt. rend. 134: 1329 (1902).
[m] Chemztg. 27: 34 (1903).
[n] Pisani, quoted by Lacroix, loc. cit.

in Scandinavia March 30, 1875, contained 1.40 per cent K_2O.[a] The Vesuvius dust of 1906 contained of K_2O, soluble in concentrated hydrochloric acid, 2.07 per cent.[b] Additional analyses of unconsolidated tuffs from the western United States give values of 1.48,[c] 2.92,[d] 3.46,[e] 4.25,[f] 4.88,[g] 5.01,[h] and 5.58[g] per cent. Four samples from the Philippines gave 1.86, 2.72, 2.84, and 3.63 per cent.[i] On the other hand, Nicholson's[j] analysis of an average sample of Nebraska tuff shows only 0.36 per cent K_2O. Whether this indicates an actual deficiency of potash in Nebraska tuffs or whether it is to be referred to error of analysis or sampling it is impossible to say.[k] The relatively high potash content of volcanic dusts can, and does, persist after the processes of metamorphism have been completed, as is shown by analyses 20, 21,[l] 22, and 24 in Table XI. In analysis 23, however (where the cement is calcareous), the potash is low, and a silicified tuff containing but 0.88 per cent K_2O has been reported from near Triberg, in the Black Forest, Germany.[m]

The appreciable quantities of phosphorus in the Pelée dust[n] and in the tuffs from Cottonwood Canyon, Idaho,[o] Owens Lake, California,[p] and Castle Hill, Maine,[q] are also of interest from an agricultural point of view. Phosphorus was also found in Krakatoa dust by van

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[a] Nordenskiöld—Met. Zs. **11**: 211 (1894).

[b] Bruttini—Boll. quindic. Soc. agric. ital. **11**: 343 (1906).

[c] From Bozeman, Mont.: Clarke—U. S. Geol. surv. Bull. **42**: 141 (1887).

[d] From Redding, Cal.: Melville—U. S. Geol. surv. Bull. **148**: 197 (1897).

[e] From Devil's Pathway, Montana: Whitfield—U. S. Geol. surv. Bull. **42**: 141 (1887).

[f] From Ravalli County, Mont.: Berry, quoted by Rowe—Univ. of Mont. Bull. **17**: 9 (1903).

[g] Downieville area, California: Steiger—Ann. Rept. U. S. Geol. Surv. **17**, I: 627 (1896).

[h] Genesee Valley, Idaho: Wedderburn—Ann. Rept. U. S. Geol. Surv. **17**, I: 627 (1896).

[i] Cox—Philip. Jour. Sci. **3**: 404 (1908).

[j] Quoted by Barbour—Proc. Nebraska acad. sci. **1894-95**: 13.

[k] Cf., however, the high value for the Harlan County tuff (analysis 10, Table X).

[l] Another analysis of tuff from near Chemnitz gives 3.90 per cent K_2O (Knop—Neues Jahrb. Min. **1859**: 575).

[m] G. H. Williams—Neues Jahrb. Min. Beilagebd. **2**: 630 (1883).

[n] Analysis 6, Table I. Griffiths (Chem. news **88**: 231 [1903]), found 0.20 per cent P_2O_5, and Wiechmann (Science (n. s.) **15**: 910–911 [1902]) found traces of phosphorus in Pelée dust. Hillebrand and Steiger (loci citati, on p. 156) each found 0.18 per cent P_2O_5 in the West Indian dust.

[o] Analysis 18, Table X.

[p] Analysis 19, Table X.

[q] Analysis 23, Table XI. Cf. also the trace of phosphorus in the sample from Marquette, Mich. (analysis 24, Table XI).

der Burg,[a] and in Vesuvius dust by Bruttini[b] and Paris,[c] and is probably quite generally present in small amounts.[d]

VOLCANIC DUST IN THE SOIL.

The potash, phosphorus, and other elements contained in volcanic dust are rapidly and easily made available for plants on account of the comparatively great solubility and rapidity of disintegration of the material, due both to its chemical composition and its physical nature. The glassy matter[e] is easily attacked by the soil solution, and the irregular form of the particles exposes a great surface to this action. The general loose structure and prevailingly good flocculation of volcanic dusts, caused by the uniform size and irregular shape of the particles, promotes the absorption and retention of moisture and allows the rapid movement of the soil solution and its contact with every soil particle. This not only promotes the disintegration of the particles, but itself assists the growth of plants in the resulting soil.

It is to be expected, therefore, that volcanic dusts would make excellent soils,[f] and such is actually found to be the case. Volcanic regions are well known to be exceedingly fertile, as, for instance, Java, Japan, the Hawaiian Islands, the vicinity of Naples, etc.[g] This, of course, is partly due to the fertility of soils derived from the decay of lavas and pumice, but no small share, at least in the maintenance of fertility, must be ascribed to the continual accretion of volcanic dust. The permanent fertility of the soils of the Limagne (France) is believed by Alluard[h] to be due to blown volcanic ash. The beds of volcanic tuff in the western United States make excellent soil and are under cultivation in many localities. Ancient soils formed from volcanic dust have been found interstratified with unaltered material in several beds of tuff,[i] indicating that the volcanic action must have been interrupted long enough to permit the formation of a soil and the production of a vegetation which was later destroyed by a renewal of the volcanic activity and covered by a deposition of a new layer of dust. So valuable are volcanic materials

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[a] Rec. trav. chim. Pays-Bas **2**: 296–303 (1883). Cf., however, note [h], p. 156.

[b] Boll. quindic. Soc. agric. ital. **11**: 343 (1906). 0.64 per cent P_2O_5 was found.

[c] Staz. sperim. agrar. ital. **41**: 321–328 (1908).

[d] Cf. the presence of apatite in several volcanic dusts, p. 153.

[e] In general about 90 per cent of the whole. See p. 152.

[f] Shaler—Ann. rept. U. S. Geol. surv. **12**, I: 242 (1892).

[g] Cf. Shaler—loc. cit., pp. 243–244; Semmola—Atti Ist. incorr. Naples **8**: 100–103 (1848); Hill—Trans. N. Z. inst. **19**: 387 (1886); de Grazia—Ann. R. Scuola agr. Portici (2) **7**: 13–26 (1907).

[h] Compt. rend. **100**: 1081–1083 (1885).

[i] E. g., in Alaska, by Brooks (Ann. Rept. U. S. Geol. Surv. **21**, II: 366 [1900]), and in Hawaii by Branner (Amer. jour. sci. (4) **16**: 315–316 [1903]).

to the soil that Rowe[a] has suggested the use of the Montana dusts as fertilizers; and Russell[b] believes that the high potash content and great fertility of the soils of Nez Percés County, Idaho, may be due to the volcanic dust which is abundant in this region. Showers of volcanic dust, when not so heavy as to smother or mechanically injure the plants, have no injurious effect on vegetation. In fact, exactly the opposite is the case. The fertilizing action of dust from the West Indian volcanoes on the soil of the surrounding islands, especially Barbados, has been noticed both after the eruption of 1812[c] and after that of 1902.[d] The great dust falls following the eruptions of Santa María did no harm, except where the plants were mechanically injured, and the fertility of the soil seemed to be increased by the volcanic increment.[e] On the island of Krakatoa, where all vegetation was destroyed by the eruption, plants had begun to take hold within less than three years, in spite of the fact that even the seeds had to be brought from elsewhere by the wind and sea and by birds.[f] In 1902 the island had again become largely covered with vegetation.[g] On the surrounding islands the Krakatoa dust did no harm to vegetation, except where the fall was heavy enough to produce mechanical injury.[h]

As a soil material, therefore, volcanic dust is of considerable importance—an importance which has been recognized by but few investigators of soil formation. Not only are there large areas in the neighborhood of active volcanoes where recent volcanic dust forms the main constituent of the soil, but there are other much larger areas over which the soil has been, and is being, formed from volcanic tuffs, and still other and yet larger areas over which wind-borne dust of recent or ancient volcanic origin is added to the soil in sufficient quantity to be worthy of consideration, particularly as a source of potassium. Those soils which have never been affected by the products of volcanic action are probably far in the minority. In our own country the volcanic soils of the Northwest form no inconsiderable portion of the arable lands.

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[a] Univ. of Montana Bull. **17**: 11 (1903).

[b] U. S. Geol. surv. Wat. supp. pap. **53**: 34 (1901).

[c] Kingsley—At last, vol. 1, p. 90 (1871), through Belt, The naturalist in Nicaragua, p. 354 (1888).

[d] Anderson and Flett—Proc. Roy. soc. **70**: 429 (1902); Teall—Quart. jour. Geol. soc. **58**: 370 (1902).

[e] Sapper—Centbl. Min. **1903**: 66–70.

[f] Treub—Ann. Jardin bot. Buitenzorg **7**: 213–223 (1888).

[g] Penzig—Ann. Jardin bot. Buitenzorg (2) **3**: 92–113 (1902). See also Ernst—Vierteljs. naturf. Ges. Zurich **52**: 289–363 (1907); and D. H. Campbell—Amer. nat. **43**: 449–460 (1909). On the analogous case of the revegetation of Pelée and La Soufrière after the recent eruptions see: Hovey—Bull. Amer. geog. soc. **40**: 662–679 (1908), **41**: 72–83 (1909).

[h] Nature **29**: 437 (1884).

Both in the past and in the present the winds have been the great agents in the distribution of volcanic materials. The area covered by material actually thrown from volcanoes is comparatively very small, but the winds extend this radius many hundredfold and it is really because of their assistance that volcanic material is of importance to soils in general. Even when the material has once been deposited the wind's action thereon has not necessarily ceased. Many beds of loose tuff in the western United States, laid down and perhaps buried in former geologic time, have been exposed by changing conditions and are again being attacked by the wind and being redistributed over the now existing surface. Among the translocating activities of the wind the movement of volcanic dust is by no means the least important.

THE WIND TRANSPORT OF VEGETABLE MATTER.

The material carried by the wind is not entirely mineral, but includes as well much vegetable matter, which is, of course, of importance in supplying humic materials to the soil. On account of their low specific gravity and usually irregular form fragments of vegetable origin are transported with peculiar ease, and especially is this true of the finer dusts. Samples of blown dusts of all sorts invariably contain plant fibers, pollen, and other organic substances, as has been shown by many microscopical and chemical examinations. Among 50 samples of sirocco dust examined by Macagno and Tacchini[a] 25 contained more organic matter than inorganic, 18 were predominantly inorganic, and 7 had approximately equal quantities of organic and inorganic constituents. The presence of organic matter in sirocco dusts has also been noticed by Sementini,[b] Reissek,[c] Arago,[d] Bouis,[e] Silvestri,[f] von Lasaulx,[g] von John,[h] Passerini,[i] Palmeri,[j] Becke,[k] Chauveau,[l] and Früh.[m] Organic material is present in cryokonite[n] and has been found in volcanic dust,[o] in dust

[a] Ann. meteor. ital. (2) **1**: 73 (1879); see also pp. 69–71.
[b] Giorn. fis. chim. stor. nat. (2) **1**: 28–32 (1818).
[c] Ber. Mitt. Freunden Naturw. **4**: 153 (1848).
[d] Oeuvres complétes **12**: 468–470 (1859).
[e] Compt. rend. **56**: 972 (1863).
[f] Atti Accad. Gioenia Catania (3) **12**: 140–141 (1878).
[g] Tschermak's min. Mitt. **3**: 526, 529 (1880).
[h] Verh. geol. Reichsanst. **1896**: 259.
[i] Atti R. Accad. econ.-agr. Georg. Florence (4) **24**: 139, 142, 152 (1901).
[j] Rend. R. Accad. sci. fis. Naples (3) **7**: 156 (1901).
[k] Anz. Kaiserl. Akad. Wiss. Vienna **38**: 108 (1901).
[l] Ann. Soc. météor. France **51**: 75 (1903).
[m] Met. Zs. **20**: 174 (1903).
[n] von Lasaulx—Tschermak's min. Mitt. **3**: 522 (1880). For definition of cryokonite see p. 103.
[o] Nordenskiöld—Met. Zs. **11**: 206–208 (1894); Rennie and Higgin—Trans. Roy. soc. South Aust. **27**: 205–206 (1903); Woolnough—Ibid., p. 207; Janežíč—Met. Zs. **23**: 224 (1906); Paris—Staz. sperim. agrar. ital. **41**: 321–328 (1908).

DAMAGE BY BLOWING OF SOIL ON STRAWBERRY FIELD NEAR SEVERN, MD.

RECENTLY PLANTED FIELD AT SEVERN, MD., NOT DAMAGED BY BLOWING.

collected from snow on top of Ben Nevis,[a] in dust from the cathedral tower at Nancy, France,[b] in dust fallen in Indiana in January, 1892,[c] and in dust from the south Russian dust storms.[d] Tissandier found that ordinary atmospheric dust contained from 25 per cent to 34 per cent of combustible organic matter.[e] The falls of pollen, etc., which occasionally occur are mentioned on page 91. Living spores or seeds of plants are always present in air dusts, and indeed many plants are largely disseminated in this way.[f]

The wind distribution of seeds, spores, etc., is not, however, of much importance to the soil, for the amount of vegetable matter so supplied is negligibly small. Much more important is the blowing about of general plant débris, and especially of dead leaves from the deciduous trees. Were it not for the action of the wind on such material a plant could supply with humus only the soil immediately beneath it. As it is, what might be called the humifying radius of the plant is greatly enlarged, and the distribution of humus throughout the soil is made much more uniform.

The quantity of such dead plant material which is blown about by the wind is a matter of common knowledge, so obvious, in fact, that it has quite generally escaped attention. It consists not only of fallen leaves, but of small twigs, flowers, fruits, seeds, etc. In some cases, as, for instance, the "tumble weeds," whole plants are blown and rolled over the surface.

There is no question that the importance of such vegetable matter to the soil is very great indeed. It has even been argued that the material derived from its decay is in large part responsible for the growth in thickness of certain deposits and the resulting burial of articles left on the surface as described on pages 106–108. This, however, seems unlikely, since the vegetable matter tends constantly to disappear, leaving no permanent residue except the very small amount of ash which it contains. The final products of the decay and oxidation are mainly gaseous. It is not probable that blown

[a] Murray and Renard—Nature **29**: 591 (1884). For another instance of organic matter in dust from snow see Nature **27**: 496 (1883).

[b] Thoulet—Compt. rend. **146**: 1347 (1908).

[c] Somers—Science **21**: 304 (1893).

[d] Klossovskĭ—Ciel et terre **15**: 564–566 (1895).

[e] Les Poussières de l'air, p. 11, 16 (1877).

[f] On the dissemination of plants by the wind see: De Candolle—Géographie botanique raisonnée, vol. **2**, p. 613–615 (1855); Kerner—Zs. deut. Alpenver. **2**: 144–172 (1871); Hildebrand—Die Verbreitungsmittel der Pflanzen, 1873; Beccari—Malesia, vol. **1**, p. 216–224 (1878); E. J. Hill—Amer. nat. **17**: 812–818 (1883); Kerner—Natural history of plants, 1st English ed., **2**: 848–862 (1895); Kronfeld—Studien über die Verbreitungsmittel der Pflanzen, 1900; Vogler—Flora **89**: 1–137 (1901); Schimper—Plant geography, Fisher's trans., pp. 79–80 (1903); Ernst—New Flora of Krakatoa, Eng. ed., pp. 60–68 (1908).

vegetable matter would cause any great growth of soil, but its importance is in no wise lessened by this fact. Rather is it increased, since the very fact that the organic matter of the soil tends to disappear makes it extremely important that this loss be made up by a continual supply of new material.

The distances to which organic matter is carried by the wind are usually not great. The activity is rather in distributing the humus-forming material over a territory a little wider than it could otherwise reach, than in supplying it to regions at a distance. It is true that individual leaves, light seeds, etc., may be carried considerable distances by the wind as is instanced by the finding of leaves on mountains and especially on the Alpine glaciers at distances up to 12 miles from the nearest possible source.[a] The soil mentioned on page 105 which was collected by Mr. Robinson from the top of Mount Monadnock in New Hampshire contains numerous twigs of spruce, though the upper limit of this tree is far below the summit. Making all possible allowances for the action of animals, many of these twigs must be regarded as carried by the wind to the situation in which they were found. This soil contains 49.95 per cent of organic matter, much of which is undoubtedly blown from the country below, though a part is probably formed in situ by mosses and similar plants whose spores have been carried up by the wind and whose growth is encouraged by the moist condition of the soil which occurs in rock basins which collect and hold the rain. All largely eolian soils in the humid regions are likely, however, to contain much organic matter,[b] as is seen in the "soils" already mentioned which are formed by the accumulation of blown material on the roofs of houses, in rain spouts, etc.

TRANSLOCATION IN GENERAL—SUPPLEMENTARY ACTION OF THE AGENTS.

In the first three chapters of this bulletin the various translocating agents were discussed, and in the succeeding chapters one of these—wind—has been shown to have a much greater importance than is usually assigned to it. For purposes of discussion it is necessary to treat the various agents separately and to discuss the work of each

[a] Schibler—Jahrb. Schweizer Alpenclubs **33**: 286 (1897–8); Vogler—Flora **89**: 83–86 (1901). Koldewey found leaves on the arctic ice 8 miles from the coast (German Arctic Exped. of 1869–70, vol. **1**, 120 [1874]). Cf. also the recorded "rains" of hay, seeds, etc., which must have come from a distance (Phipson—Compt. rend. **52**: 108–109 [1861]; Benson—Nature **12**: 279 [1875]; Nature **12**: 298 [1875]; Galton—Nature **44**: 294 (1891); Berti, in Tacchini—Rend. Accad. Lincei (5) **6**: 299 [1897]; Symons's Meteor. Mag. **32**: 106–107 [1897]).

[b] Fischer suggests that the high content of organic matter of the black earth ("tirs") of Morocco may be due to accretions of vegetable dust (Mitt. geog. Ges. Hamburg **18**: 154 [1902]). It may be permissible to ascribe a similar origin to the organic matter of the chernozem.

as though it were distinct and independent, but the translocation which actually takes place in nature is seldom so simple as this. All the agents, and especially wind and water, are constantly interacting in the most complex manner, with the result that nearly all translocated material has been moved by both wind and water and frequently by other agents as well.[a] Sometimes the movement is mainly eolian; sometimes it is mainly aqueous, but almost always it is something of both. The translocation going on on the earth's surface is the result of all the actions of all the various agencies—a system of actions usually so complex as to defy detailed analysis.

This mutual action of wind and water is well exhibited in translocation by rivers. In the first place, much of the river's load is supplied by eolian action. It has been pointed out on page 20 that the river itself is able to attack only its bed and banks, and that its detrital load is supplied mainly by rain wash and by the wind. In some regions the wind supplies nearly all the load.[b] The assistance of the wind does not, however, stop with the supply of material, but is of even greater importance in distributing over the flood plain the material which the river has brought down. All streams throw up sand and mud along their banks and deposit sediment during freshets, all of which material soon dries and is scattered by the wind over the surrounding country, this being the only way in which the detrital material of a river can be distributed over territory not reached by its waters.[c] Sometimes this material is sandy and is supplied in sufficient quantities to form dunes, producing the well-known river dune systems, which in general are composed of material representing the whole drainage area of the river.

The same conditions apply to coastal dunes. They are made up of material from hundreds of sources—the detritus supplied by rivers, débris from the wave erosion of the coast, bits of shells, fragments of pumice and volcanic dust, etc. Sometimes the sands of the coastal dunes have been so much worked and pounded by the waves that practically nothing but quartz remains, but usually the sands are newer and show traces of their origin, or rather of their origins. Cobb[d] thinks that the dune sands of Hatteras are glacial débris

[a] The origin of loess, as discussed on pp. 129–141, furnishes an excellent example of this complexity.

[b] See Shaler—Bull. Geol. soc. Amer. **10**: 247 (1899).

[c] For examples of this process of wind distribution of river-borne sediment, see Hewitt—Proc. Liverpool Geol. Soc. **7**: 22–24 (1892); Blake—Quart. Jour. Geol. Soc. **53**: 241–242 (1897); Walther—Wüstenbildung, p. 119 (1900); Lomas—Rept. Brit. Assoc. **1903**: 654–656; Davis—Carnegie Institution of Washington, Pub. **26**: 60–63 (1905); Ferrar—Survey Notes (Egypt) **1**: 18–20 (1906); Huntington—Pulse of Asia, p. 103 (1907); Stein—Ancient Khotan, pp. 124–125, 198, Appendix G (1907).

[d] Jour. Elisha Mitchell sci. soc. **22**: 17–19 (1906), Nat. geog. mag. **17**: 314, note (1906). For the similar case of the dune sands of Holland, see Retgers—Ann. École polyt. Delft **7**: 1–50 [1891]. Cf. also: Thoulet—Compt. rend. **144**: 938–940 (1907).

from the New England granites, scraped off by the ice sheet and worked southward along the coast by waves set up by the prevailing winds. A very striking example of the complexity of movement displayed by translocated material was observed by Sickenberger.[a] A hornblende-rich sand was produced by the weathering of the hornblende granites of Assuan in Egypt, was carried down to the Mediterranean by the Nile, moved by the coastal current 150 miles to the east to El Arish, where it was thrown upon the beach, picked up by the winds, and blown inland in a line of dunes. This was a journey of over 700 miles by river, ocean, and wind.[b] There is no reason to believe that this case is unusual in anything except the possibility of identifying the material and tracing the path it had traveled.[c]

The dunes represent only the coarser material deposited by the river. The finer mud and silt are blown clear away (when dried) and widely distributed over the valley and the adjoining uplands. Virlet d'Aoust[d] (as already mentioned) found high on the mountains of Mexico eolian soils entirely composed of the material of the river-deposited alluvium of the valleys.

EXCESSIVE BLOWING OF THE SOIL.

The moderate amount of wind movement of the soil which is normal to most agricultural areas is, on the whole, beneficial, because of the resultant increase (or maintenance) of heterogeneity and the supply of minerals which might otherwise be deficient.[e] Under exceptional conditions, however, it is possible for the erosive activity of the wind to become so excessive that both the soil and the plants it supports are seriously injured.[f] The damage caused in some places by

[a] Quoted by Walther—Wüstenbildung, p. 118 (1900).

[b] On the similar case of magnetite from the Pyrenees in the dunes of Gascony, see Fabre—Bull. geog. hist. descrip. **1902**: 132–148, and authorities there cited.

[c] On the possibility of identifying sand grains (by their internal character) and tracing their history, see Mackie—Trans. Edinb. geol. soc. **7**: 148–172 (1897).

[d] Bull. Soc. géol. France (2) **15**: 129 et seq. (1857).

[e] Another occasionally important beneficial effect of wind action on the soil is the improvement of physical condition due to the addition of blown sands to heavy clays. For examples, see p. 124 above.

[f] For instances of damage by extreme blowing of soil see T. Dwight—Travels in New England, vol. **2**, p. 494, vol. **3**, p. 91–92 (1822); Studer—Lehrbuch der physische Geographie und Geologie, vol. **1**, p. 334 (1844); Pacific Rural Press **11**: 37, 60 (1876), **19**: 200 (1880), et al.; Reid—Geol. Mag. (3) **1**: 167 (1884); H. T. Fuller—Bull. Geol. soc. Amer. **3**: 148–149 (1892); W. C. Knight—Wyo. agr. expt. stat. Bull. **14**: 104 (1893); F. H. King—Wisc. agr. expt. stat. Bull. **42**, 1894; Vysotskĭĭ—Trudy Eksped. Ross. Lĭesn. Dept. **1**: 33–48 (1894); Abbe—Mon. weath. rev. **23**: 19 (1895); Bĭeletskĭĭ—Mater. isuch. russ. pochv **9**: 1–40 (1895); Payne—Col. agr. expt. stat. Ann. rept. **9**: 184 (1896); Shaler—Bull. Geol. soc. Amer. **10**: 245–252 (1899); Rept. Roy. comm. on condition of crown tenants, New South Wales **1**: viii, 24–26 (1901); Woeikof—Ann. géog. **10**: 113 (1901); Emeis—Allg. Forst.-Jagdztg. **78**: 401–414 (1902); McMaster—Jour. Proc. Roy. soc. N. S. Wales **37**: 138–145 (1903); Heintz—Poln. entsik. russ.

wind removal of soil is quite comparable to that produced in other localities by water erosion, and consists not only in the loss of the soil material itself, which is usually relatively unimportant, but much more largely in the removal of soil from around the roots of plants, causing their death or loosening them, so that they themselves can be blown away. The extent to which this removal of the soil may sometimes go is illustrated by the tree shown in Plate II, figure 1, which has had several feet of soil removed from around its roots.[a] The great dust storm of May 6–7, 1889, in the Middle West removed the soil in some places to a depth of 5 or 6 inches.[b] Noble[c] records the wind removal of 1 foot of soil from an area of over 100,000 acres in Australia. During the dust storms of the spring of 1894 in the south of Russia the soil was removed to an average depth of about 6 inches, and nearly 200 square miles under cereal crops were ruined.[d] According to information obtained by Huntington[e] the spring winds in the Turfan basin (Asia) not infrequently remove 2 or 3 inches of soil.

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selsk. khoz. **8**: 50–51 (1903); Kearney—U. S. Dept. Agr. Bur. plant ind. Bull. **86**: 15, 22 (1905); I. A. Williams—Iowa Geol. surv. **16**: 497 (1905); Hart and Gleason—Bull. Ill. State Lab. nat. hist. **7**: 164–171 (1906); Hertzberg—Deut. landw. Presse **33**: 368–369 (1906); Prometheus **18**: 54–55 (1906); Hilgard—Soils, p. 9, (1907); C. G. Hopkins and Pettit—Ill. agr. expt. stat. Bull. **123**: 246 (1908); W. H. Stevenson, Schaub, and Snyder—Iowa agr. expt. stat. Bull. **95**: 14 (1908); C. B. Smith—U. S. Dept. agr. Farmers' Bull. **323**: 15–18 (1908); Reagan—Science (n. s.) **28**: 653–654 (1908); Hazen—U. S. Dept. Agr. Bur. Plant Ind. Bull. **130**: 51–53 (1908); Gill—Jour. Dept. agr. South Aust. **11**: 1028–1031 (1908); Wright—ibid. **13**: 235–237 (1909); Oklahoma City Farm journal, March 15, 1909; Scofield and Rogers—U. S. Dept. Agr. Bur. Plant Ind. Bull. **157**, especially p. 10 (1909); Hunter—ibid. Pub. No. **495** (1909); Alway—Nebraska agr. expt. stat. Bull. **111**, 1909; Beadnell—An Egyptian oasis, p. 198–211 (1909); Simmons—Nebraska Farmer **49**: 431 (1910); Helder—Bull. Dry Farming Congress **3**: 318 (1910); and Field Operations, Bureau of Soils, **1900**: 390; **1901**: 528, 544; **1902**: 470, 471, 473, 743, 753, 781–782; **1903**: 116, 150, 174, 954, 1035, 1054, 1059, 1270–1272; **1904**: 63, 699, 760, 782–783, 902–904, 1140–1141; **1905**: 769, 901, 935; **1906**: 268, 469, 571, 579, 748, 843–844, 938, 976, 979; **1907**: 319–320, 341, 635, 823–824, 915–916, 918, 921.

[a] This tree stands in Whiteside County, Ill. A photograph of another and even more striking example which occurs in central Australia is given by Benbow—Agr. gaz. New South Wales **12**, facing p. 1252 (1901). Other photographs of similar phenomena are given by Flerov—Schr. naturf. Ges. Univ. Dorpat **10**, I: facing p. 296 (1902); Coulter—Proc. Ind. acad. sci. **1906**: 127; Britton—Bull. Torrey bot. club **30**: plate 25, and p. 573 (1903); and Zavitz—Rept. on reforestation of waste lands in southern Ontario, p. 8, 28 (1909).

[b] Amer. geol. **3**: 398 (1889).

[c] Mon. weath. rev. **32**: 364 (1904). On the damage by soil drift in Australia see also Rept. of Commission on condition of crown tenants, New South Wales **1**: 24–26 (1901).

[d] Klossovskĭ—Ciel et terre **15**: 561 (1895); Heintz—Poln. entsik. russ. selsk. khoz. **8**: 50–51 (1903).

[e] Pulse of Asia, p. 300 (1907).

Nor does the damage stop with the removal of the soil. The blown material collects on the fields to leeward and frequently causes more injury to the crops upon which it is deposited than was caused by the removal from its original location. Grain and other standing crops are especially liable to damage in this way, though in this case it is probable that the damage is due not so much to the deposit of the blown material on the plants as to the cutting action of the flying grains of sand.[a] Blown sand has been known to injure trees severely and even to kill them, and its effect on green plants is naturally even more injurious. In addition, however, to the cutting action there is a good deal of actual burial of young plants growing close to the ground.

Damage by both erosion and deposition may occur on the same field, as is shown in Plate III, where some strawberry plants have been blown entirely out of the soil while others have been buried. The damage done in this case can be better appreciated by comparison with Plate IV, which shows a portion of the same field planted just before the photograph was taken, and not yet subjected to severe wind action. This portion of the field is seen also in the upper left-hand corner of Plate III. Plate V shows a field on the same soil, where the blown sand has drifted in between the rows of plants.

In all cases the damage by blowing is more largely to the crop than to the soil. Plants are blown out, buried, or mechanically injured, but the soil itself is usually not greatly affected. In some cases, of course, soil is blown entirely away in sufficient quantity to constitute a serious loss, but such cases are not the rule, and even then the loss is usually not permanent, being made up sooner or later by a balancing deposition; and, on account of the usual fertility of the wind-deposited material, such deposition is in most cases beneficial to the soil, whatever may be its effect on the crop.[b] In some few cases the deposited material may be injurious, as, for instance, certain industrial dusts, the dust of smelter smoke, etc.[c]

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[a] Hooker—Gardener's chronicle (2) **9**: 12 (1878); Paletskĭĭ—Fixation of sand (*Russian*), p. 22 (1901); Udden—Pop. sci. mon. **49**: 663 (1896); Cowles—Bot. gaz. **27**: 108 (1899); Harshberger—Proc. Acad. nat. sci. Phila. **1900**: 626; Brockmann-Jerosch and Heim—Vegetations-bilder **6**, Heft 4 (1908); Olsson-Seffer—Bot. gaz. **47**: 116–117 (1909). Even blown snow crystals have been known to kill trees (C. King—Exploration Fortieth Parallel, vol. **1**, p. 527 [1878]).

[b] When the subsoil is well weathered and of good quality, and when the generation of humic matters is easy, even a not too great removal may be beneficial by progressively lowering the zone of root activity and adding fresh soil material thereto. See Menzel—Kosmos **2**: 239 (1905).

[c] Haselhoff and Lindau—Die Beschädigung der Vegetation durch Rauch, 1903; Haselhoff—Landw. Vers. Stat. **67**: 157–206 (1907), **69**: 477–482 (1908); Fühling's landw. Ztg. **57**: 609–615 (1908); Ebaugh—Jour. Amer. chem. soc. **29**: 951–970 (1907); Frazer—Trans. Amer. inst. min. engs. **38**: 498–555 (1908); Cohen and Ruston—Nature **81**: 468–469 (1909); Formad—Ann. Rept. Bur. Animal Industry, U. S. Dept. Agr. **25**: 237–268 (1908).

In this last case, however, the observed damage has been shown[a] to be more largely due to the gaseous constituents of the smoke than to its suspended solids, and in any case the injury to the soil from such sources is of vanishing importance.[b] It has been claimed by Tacchini[c] that sirocco dust is injurious to plants upon which it falls, but from his statements it seems probable that the injuries were due rather to the hot, dry winds which accompanied the falls of dust than to the dust itself. It has already been pointed out that the material carried by dust storms is in general markedly beneficial to plants and to the soil, and there is no reason why the properties of the sirocco dust should be exceptional.[d] But, though the injury to the soil is seldom grave or permanent, excessive blowing is nevertheless very serious and very harmful because of the direct effect on the crop. This is particularly the case if the blowing occurs on recently seeded fields or where the plants are young, and unfortunately there are many parts of this country in which violent winds are to be expected just at this season. Throughout the arid and semiarid West, now being rapidly brought into cultivation, soil blowing has been found a most serious problem, and is demanding the best efforts of agriculturists in the attempt to minimize its ravages. In these regions nearly all the types of soil are likely to be affected, but in the more humid areas of the East, wind damage is mainly confined to sands, and in fact even in arid climates the maximum of blowing is usually encountered on such soils and on those composed of silt particles more or less uniform in size. The greater blowing of sandy soils is largely ascribable to the moisture relations already discussed on page 130 in connection with the wind-damaged sands of Anne Arundel County, Md.

In Table XII are given the mechanical analyses of a number of soils which have been found to blow badly.[e] The analysis of a soil

[a] Haywood—U. S. Dept. Agr. Bur. chem. Bull. **89**, 1905, and Bull. **113**, 1908, with references there cited.

[b] See Widtsoe—Utah agr. expt. stat. Bull. **88**: 149–164, 177–179 (1903); Haywood—Science (n. s.) **26**: 476 (1907).

[c] Compt. rend. Assoc. franç. avan. sci. **7**: 477 (1878). Ivchenko speaks also of a "burning" of vegetation by the blown dust of the steppes (Ann. géol. min. Russ. **7**, I: 230 [1904]). On injury by the "mgla" or dust fog of southeastern Russia see Ivanov—Vĭestn. selsk. khoz. **1903** No. 9.

[d] Plants are sometimes injured by air-deposited dusts through the "setting" of the latter into an impervious or rigid coating on the leaves and other parts, clogging the stomata and interfering with growth. This has been observed in the case of volcanic dust by Sands (Agr. news **5**: 381 [1906]) and Bruttini (Boll. quindic. Soc. agric. ital. **11**: 343 [1906]), and in the case of dust from a cement mill by Peirce (Science [n. s.] **30**: 652–654 [1909]).

[e] Nos. 1 to 4 are analyses already published by the Bureau of Soils, as follows: No. 1, Field Operations **1901**: 529; No. 2, ibid. **1907**: 916; No. 3, ibid. **1906**: 845; No. 4, ibid. **1906**: 571. Sample No. 5 was collected by the writer. No. 6 was furnished by Mr. T. H. Means, U. S. Reclamation Service. No. 7 was furnished by Mr. C. K. McClelland, superintendent of the Kansas experimental farm at Hays, to whom I am also indebted for information with regard to soil blowing in this locality. (See also Hazen, loc. cit. on p. 165.)

from the Maryland locality, just mentioned, has already been given in Table I, on page 30. Nos. 1, 2, 5, and 6 are typical of the easily attacked sands, which are of frequent occurrence. No. 6 also contains some volcanic dust, which makes it still more susceptible to attack. Nos. 3 and 4 represent the fairly uniform fine sands which

TABLE XII.—*Mechanical analyses of soils subject to blowing.*

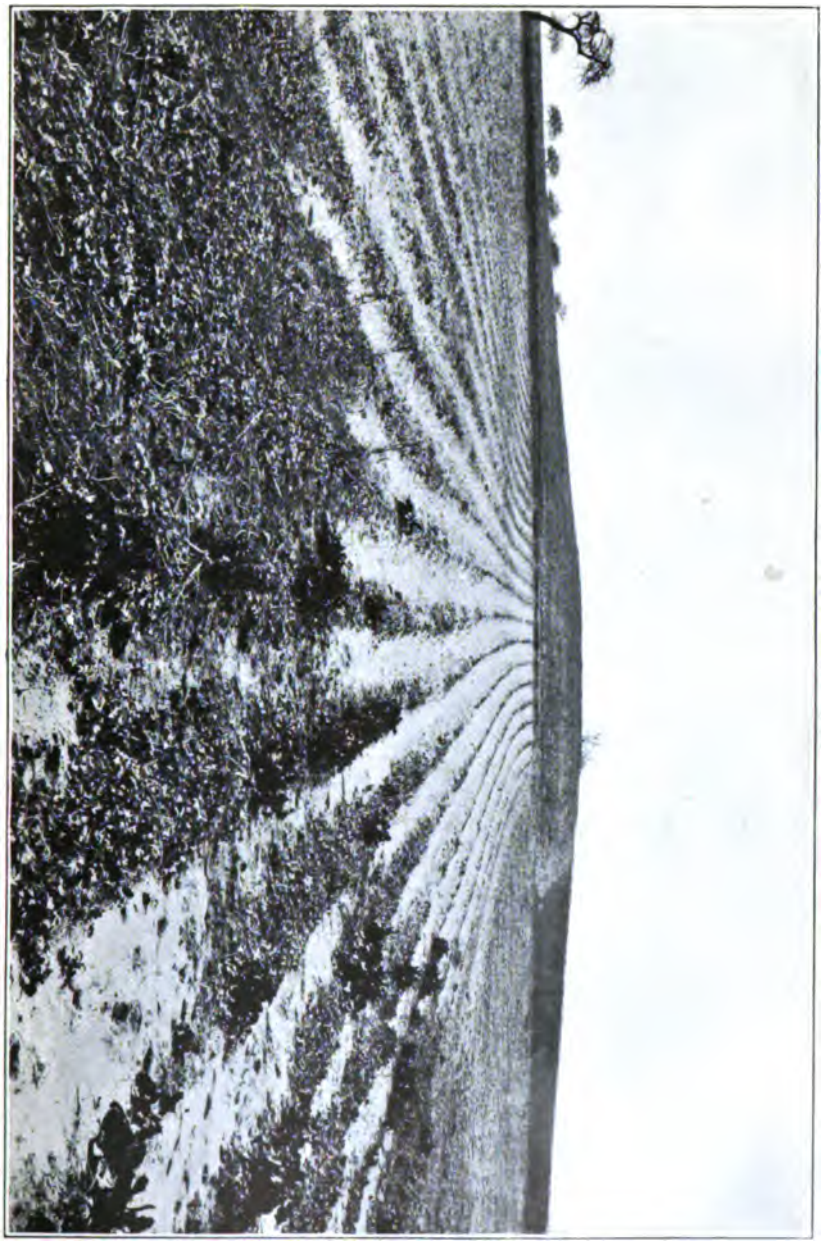
Constituent.	Ventura County, Cal.	Minidoka, Idaho.	Blue Earth County, Minn.	Oklahoma County, Okla.	Hermiston, Oreg.	Fallon, Nev.	Hays, Kans.
	1.	2.	3.	4.	5.	6.	7.
Gravel (2 to 1 mm.)	2.5	0.1	0	0.3	0	1.5	0
Coarse sand (1 to 0.5 mm.)	10.2	9.5	1.3	2.7	7.6	14.0	1.0
Medium sand (0.5 to 0.25 mm.)	37.1	16.7	5.5	15.5	17.8	15.1	.2
Fine sand (0.25 to 0.1 mm.)	31.1	61.9	64.7	60.9	52.5	42.5	1.5
Very fine sand (0.1 to 0.05 mm.)	10.0	8.5	9.3	14.7	21.4	13.4	14.0
Silt (0.05 to 0.005 mm.)	4.6	1.4	10.8	3.8	.4	10.5	65.8
Clay (below 0.005 mm.)	1.9	2.6	8.3	2.3	.5	3.0	17.8

have proven quite troublesome at several points in the humid regions. No. 7 is of the silty type, which blows badly when too dry or lacking in organic matter. In this soil the content of so-called "colloidal" clay,[a] as distinguished from material which is simply less than 0.005 mm. in diameter, is probably very low.

Of course the mechanical composition of a soil is not by any means the only factor affecting its susceptibility to blowing, and in fact in many cases it is not even the controlling one. The magnitude and constancy of the water content, the presence or absence of organic matter, and other less important factors come into play, and indeed in practice the occurrence or nonoccurrence of excessive blowing is usually controlled by factors altogether external to the soil and including as most important the strength and seasonal relationship of the winds, the topography (with relation to the active winds), and the character and permanence of the vegetal cover. The characteristics of vegetation and of moisture in protecting soils from wind action have already been fully discussed on pages 28 to 31.

The processes of cultivation naturally tend to increase the degree of exposure of the soil to wind action, and in regions of strong winds it not infrequently happens that when the soil is broken preparatory to cultivation much of it is blown away. The removal of the natural vegetal cover for purposes of cultivation is necessary, and any soil loss which may be occasioned thereby must be regarded as an unavoidable concomitant of agriculture, but the destruction of the vegetation and consequent loss of soil is as often the result of misuse of the land as of its use. For instance, the overworking of

[a] Hilgard—Soils, pp. 59–62 (1907).



SAND DRIFTED BETWEEN ROWS OF PLANTS, SEVERN, MD.

pasture land will often so thin the grass that, with the advent of a dry season, it dies and erosion by both wind and water is greatly increased.[a]

Neither is the loss of soil which so often follows the initial clearing of western lands always entirely unavoidable. The damage is frequently due to clearing at the wrong season or to clearing in too large portions or too long before the land is ready for crops. In areas where soil drift is to be feared, the land should be exposed no more than is necessary, and, if possible, never at the season of heaviest winds. The native vegetation should be left on the land until everything is ready for culture, and if the crop planted is at all slow-growing, it will frequently pay to plant also some quick-growing and easily rooted crop in order to tide over the period of exposure between the clearing and the establishment of a more permanent crop (as, e. g., alfalfa). Rye has been found useful in this way in some regions. Often it will pay to adopt the expedient of clearing the land only in alternate strips 20 to 30 feet wide and at right angles to the prevailing direction of the dangerous winds. The strips of native vegetation thus left will protect the cleared strips until the latter can be put into cultivation, and when this is accomplished the uncleared strips may be cleared in their turn, being now protected by those upon which the planted vegetation has taken hold. This scheme, variously modified, has proven of great service in many cases.

On irrigated farms, where arrangements must be made for the distribution of water, the necessary leveling often forbids the leaving of native vegetation, or clearing it only in strips. Even in these cases, however, it will be found wise to clear in as small areas as circumstances will permit and to leave occasional strips of the native brush wherever the configuration of the ground makes it possible. Temporary cover crops will also be found useful, and in sage-brush sections the covering of the surface with the uprooted bushes has a considerable protective value. By the use of such precautions and the general exercise of common sense in the time and manner of clearing, wind damage can be greatly reduced even on lands where general clearing and leveling is deemed necessary.

The between-crop cultivation of years following that of initial clearing must also be designed to leave the soil exposed as little as possible, and that at the season when wind movement is as nearly as possible at a minimum. It is usually not difficult to design a cultural routine which will meet this requirement under any given conditions. Fortunately, each year of use will, if the cultural scheme be properly

[a] Fuller—Bull. Geol. soc. Amer. **3**: 148–149 (1892); Forbes—Ariz. agr. expt. stat. Bull. **38**: 249–255 (1901); Burgess and Coffey—Field Operations Bureau of Soils **1904**: 903; Worthen and Eckman—ibid. **1907**: 824; Gill—Jour. Dept. Agr. South Aust. **11**: 1028–1029 (1908); Wright—ibid. **13**: 235–237 (1909).

designed and carried out, add more organic matter to the soil, decrease its sandiness, and put it in better shape to withstand the attack of the wind. Wind drift is very largely a trouble of the new soils, and it is largely because of the great amount of arid soil just now being broken for use that the subject attracts so much present interest. However, if the cultural routine is to improve the soil it must be designed with this in view, and on all sandy soils, arid and humid alike, the danger of wind-drift should be always in mind in designing the system of cultivation.

Another cause of wind damage has come with the recent spread of the methods of "dry farming" over the semiarid West. A part of these methods is the use of the dust mulch, and this use has brought its accompanying disadvantage, for the surface layer of loose dust thus produced is readily attacked by the wind, and the entire mulch of a field may be stripped off by a single storm.[a] On soils where the physical texture will permit, a granular or clod mulch may be maintained instead of one of dust. This not only decreases wind attack but is more satisfactory in every way. But on sands and some loams this is impossible, and in these cases, if wind damage is to be feared, the mulch must be abandoned or the field covered with straw or brush. Such a layer will furnish an efficient protection and under it a dust mulch will rest undisturbed.

This last procedure, however, belongs to a class of preventive agents whose expense precludes their use under ordinary circumstances. Here also belong the incorporation of clay with the sand,[b] the addition of large quantities of stable manure, etc. These things are of unquestioned value, but too costly for most fields. In general on soils which have been found in practice to be subject to serious blowing the economical restriction and prevention of the evil is likely to be largely a matter of properly arranging the cultural routine. Every effort should be made to maintain an adequate content of organic matter and if possible to have the land covered during the windy season with some close-growing crop which will keep the wind from the soil surface. If the summer fallow is found to induce extensive blowing, it can in many cases be abandoned in favor of a leguminous crop which is afterwards plowed under, performing the triple function of preventing wind erosion, adding organic matter, and supplying nitrogen. Where a sufficient supply of irrigation water is available, easily blown soils should be kept moist during the

[a] Hazen—U. S. Dept. Agr., Bur. Plant Ind. **130**: 51–53 (1908).

[b] This is sometimes economically possible where the clay (or silt) can be added as material suspended in irrigating water. (See Holmes and Mesmer—Field Operations, Bureau of Soils, **1901**: Plate LXXXIII; McLendon and Jones—ibid. **1906**: 579.) In this case care must be taken to prevent injury to the soil through the deposition thereon of an impervious layer of silt. See Forbes—Ariz. agr. expt. stat. Bull. **53**, 1906.

season when such damage is to be apprehended. In many cases damage may be avoided by the proper timing of the plowing, harrowing, and similar cultural operations, or by the employment of other operations, such as rolling, etc., which tend to compact the surface.[a]

Without full knowledge of the special local conditions, it is of course impossible to say just what procedure will be best under any particular set of circumstances. Climatic, biologic, and economic factors must be taken into account, and the general principles as above outlined must be modified and adjusted to each individual case. There are unquestionably circumstances under which the prevention of wind erosion is not possible, with due regard to economy; but even in such cases the damage can usually be reduced by a little care and forethought and at slight expense.

When the crop is valuable in relation to the land covered, it is frequently advisable to employ lines of trees, hedges, fences, or other obstacles which can act as wind-breaks.[b] If set sufficiently close together they will entirely prevent damage to the crop, either by wind erosion of the soil, by the drying action of hot winds,[c] or by the direct mechanical action of the wind itself.[d] In a field protected by wind-breaks there is, however, a considerable proportion of idle land, consisting not only of the land actually occupied by the trees or

[a] On cultural operations to prevent blowing see King—Wis. agr. expt. stat. Bull. **42**, 1894; Smith—U. S. Dept. Agr. Farmers' bull. **323**: 17–18 (1908); Reagan—Science (n. s.) **28**: 653–654 (1908); Wright—Jour. Dept. agr. South Aust. **13**: 235–237 (1909); Brand and Westgate—U. S. Dept. Agr. Bur. plant ind. Circ. **24**: 13–14 (1909).

[b] On wind-breaks see Bernhardt—Landw. Jahrb. **3**: 449–454 (1874); Lake—Washington agr. expt. stat. Bull. **3**: 60–63 (1892); King—Wisconsin agr. expt. stat. Bull. **42** (1894); Vysotskĭĭ—Trudy Eksped. ross. Lĭesn. dept. **1**: 33–48 (1894); Payne—Ann. rept. Colorado agr. expt. stat. **9**: 184 (1896); Card—Nebraska agr. expt. stat. Bull. **48** (1897); Kellogg—U. S. Dept. Agr. Forest service Bull. **52** (1904); Green—Farm wind-breaks and shelter-belts (1906); Hertzberg—Deut. landw. Presse **33**: 368–369 (1906); Smith—U. S. Dept. Agr. Farmers' Bull. **323**: 15–18 (1908); Hunter—U. S. Dept. Agr. Bur. Plant Ind., Pub. **495**: 10–11 (1909). On the use of fences, etc., for similar purposes see Hedin—Genom Khorasan och Turkestan, vol. **1**, p. 239 (1892); Millar—Chambers's Jour. (6) **8**: 237 (1905); Willey—Sci. Amer. supp. **65**: 120–121 (1908); Beadnell—An Egyptian oasis, pp. 207–210 (1909); Vischer—Geog. jour. **33**: 241–266 (1909).

[c] King—loc. cit., thinks that wind damage is largely due to this drying action. See also Hensele—Forsch. Geb. Agr. Phys. **16**: 311–364 (1893); Bĭĕletskĭĭ—Mater. izuch. russ. pochv **9**: 1–40 (1895).

[d] On the action of wind on vegetation see: Klinge—Bot. Jahrb. **11**: 304–312 (1889); Hansen—Die Vegetation der ostfriesischen Inseln, 1901; Früh—Jahresb. geog.-ethnog. Ges. Zurich **1901–2**: 56–153; Flahault—Géographie **5**: 357, 359–360 (1902); Hansen—Flora **93**: 33 (1904); De Bruyne—Handel. Vlaamsch natuurgeneeskundig Congres **8**: 54–59 (1904); Geinitz—Naturw. Wochens. **19**: 1025–1031 (1904); Devaux—Proces-verb. Soc. sci. phys. nat. Bordeaux **1904–5**: 58–62; Noll—Sitzungsb. naturh. Ver. preuss. Rheinl. Westf. **1907** (A): 58–68; Emeis—Allg. Forst.-Jagdztg. **83**: 1–5 (1907).

hedges, but also of the contiguous shaded portions which are thus rendered less productive; and this necessary loss of effective field area restricts the use of wind-breaks to cases of intensive cultivation of valuable crops. The use of wind-breaks must be thorough and comprehensive if it is to be of value. A single line of trees may do more harm than good, for sand drifting in from unprotected areas will collect behind it and ruin both crop and land. This is well illustrated in Plate II, figure 2, showing drift sand collected behind a fence at Hermiston, Oreg.[a]

Where the use of the land is not desired, the only necessity being to prevent its migration into adjoining areas, the usual methods of dune fixation as already outlined may be employed, due regard being had to the local conditions. In these cases grassing or forestation, usually the latter, will be found the best method of control. Similar methods can be used to prevent wind scouring of road ditches, the banks of irrigation canals and similar works. Here the various small bushes, such as the willows and tamarisks, have proven very useful. Rye has been much and successfully used for temporary fixation until bushes could be successfully started.

CONCLUSION.

Of the many standpoints from which it would be possible to view the known facts of the action of wind on the solid matter of the earth's surface, but three have received attention in the foregoing pages—the geologic, the agronomic, and that of the student of soil formation. Of these the general geologic aspect as been accorded but passing notice. and the agronomic, though briefly outlined in the last chapter, must await detailed discussion elsewhere. The main emphasis has been laid upon the action of the wind in soil genesis, and this bulletin is an effort to present the pertinent facts in their influence on our conception of the ways in which soils are made and changed. If the argument here advanced can be condensed into any one conclusion, it is simply that in these matters the wind has no minor rôle, and is not the least of the great dynamic agents which we now know affect the soil, and whose recognition has rendered no longer tenable the older static conceptions.[b] But to say that wind is important does not apply that it is most important. There are many agents which move the soil, and the one which is dominant here and now may not be dominant there and then. There are, of course, individual cases in which the soil may be labeled as mainly water-laid, or mainly eolian, or mainly the product of this

[a] Another photograph showing this condition is published in the Field Operations of the Bureau of Soils **1901**: Plate LXXXIII.

[b] Cameron—Jour. indus. eng. chem. **1**: 806–810 (1909), Jour. phys. chem. **14**: 320–372, 393–431 (1910).

or that other agent, but the histories of most soils are not to be read so easily, and general comparisons are of little value. To decide, for example, whether in the whole world wind or water moves and lays the more soil is quite impossible and almost equally useless.

The soil-forming actions of the wind may be classed roughly under two headings, soil removal and soil mixing. In removal the wind is but one of several agents (of which running water is probably the chief) which, by removing weathered soil material from the land surface into the sea, progressively expose the rocks beneath to the processes of decay, enabling the maintenance of that balance upon which depends the permanence of the soil layer. Among these agents the wind is greatest only in areas of considerable aridity, and even there it is by no means the sole active factor. From our present viewpoint, the second or mixing action is of far greater and more general importance. The carrying of soil material from place to place across the land surface makes possible, as already discussed, the existence in any particular soil of minerals not present in its parent rocks, and is one cause of the well-known and remarkable constancy with which the useful minerals occur in the soils of the world. In this action the wind shows its greatest effectiveness. As a mixer of soils already formed it yields to none. Nor is this action, like the former, confined to arid lands. The foregoing pages should serve to show that even in humid regions there is much movement of soil by wind and that soil mixing by such movement is a factor which must not be neglected. Wind action, both in removal and transfer, must be regarded as an important item in the newly emphasized dynamic explanations of the soil and its fertility.

BIBLIOGRAPHY OF EOLIAN GEOLOGY.

By S. C. Stuntz and E. E. Free.

The list of references following forms a fairly complete bibliography of eolian geology, especially of deflation and those other phenomena closely connected with the subject-matter of the bulletin. Little effort has been made to attain completeness on the less closely related lines, such as the occurrence and distribution of dunes, dune control, and general geology of deserts, the occurrences of the loess, volcanic dust, etc. Sufficient references are given on those subjects, however, to introduce the reader to the literature, and it is believed that all important articles specifically concerned with eolian action have been included. Many very important references, even in the lines most completely covered, have been omitted, or cited only as "quoted by" another writer, because it has been found impossible to verify them. Some few references have been included without verification where the information was complete enough in regard to them. Most writers, however, even of high scientific reputation, and practically all reviewers, in making references either translate or omit titles altogether, or give them only in brief, and give only date of publication or page references instead of full and exact volume, page, and date statistics. For this reason many articles which could not be found in American libraries have of necessity been omitted. Practically every reference given has been verified by one of the two compilers, usually by both, and the others are given only on good authority, such as the Royal Society Index or the International Catalogue of Scientific Literature.

The form of reference is that now generally used—author, title in full without abbreviation, standard abbreviation for the name of the periodical, and in the following order: Series number in parentheses, volume number in heavy-faced type, colon, followed by the inclusive pages of the article with its discussion, closing with the date of publication in parentheses. Where volume numbers are not used, the year is given in heavy-faced type, and in case of annuals, reports, etc., reading "for the year ——," the date of the volume rather than the usually later date of publication is given in parentheses. In some cases, however, the latter is also given where the year is used as volume number. "Part" or "Abtheilung" is expressed in Roman notation. The abbreviations for the titles of journals used in the International Catalogue of Scientific Literature have been found in some cases either too cumbrous or not sufficiently clear, so that a system of our own has been employed. It is believed that all are easily intelligible.

The titles are arranged chronologically under authors' names, and those in languages other than modern European or Latin are given in translation into some one of these languages, preferably the one in which an abstract is published, either with the article or in a place cited. Translations are also given for the Russian and Hungarian titles. Anonymous articles are entered under the titles with reference from the name of the periodicals in which they were published. The locations of translations, abstracts, and reviews, usually not mentioned in the text, are given whenever convenient and in the usual form.

The numbers following the references refer to the pages of the text upon which they are cited. The location (in the text) of the most comprehensive analysis of any paper is indicated by the italicizing of that page number. It is therefore possible not only to use the bibliography as an author index to the bulletin, but also to obtain by the joint use of it and the text synoptic information concerning many of the articles cited. The literature of any special subject can be found through the subject index by examining the pages of the text upon which that subject is treated.

Though every care has been taken to avoid errors, it is practically impossible to make any bibliography either entirely correct or entirely complete. The compilers will be very glad to be notified of any errors in citation, or of any additional titles which should be included.

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